$B_s \to \mu^+\mu^-$ versus Direct Higgs Searches at Hadron Colliders

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Presented at the Fermi National Accelerator Laboratory, October 5 (Thursday), 2006.

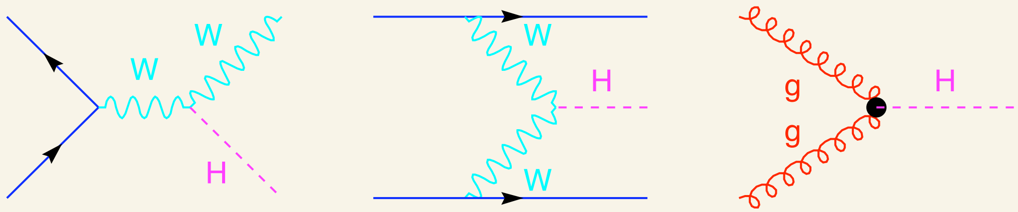
$B_s \to \mu^+\mu^-$ versus Direct Higgs Searches at Hadron Colliders

- Based on a recent paper by C. Kao and Y. Wang, Phys. Lett. B **635** (2006) 30.
- Direct search for Higgs bosons at the LHC
  $pp \to b\phi^0 \to b\mu^+\mu^- + X, \phi^0 = H^0, h^0, A^0$
- Indirect search for Higgs bosons in
  $B_s \to \mu^+\mu^-$

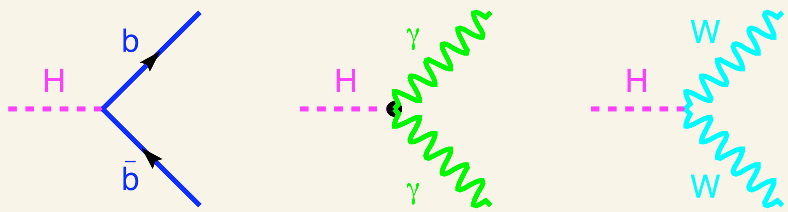
The Standard Model Higgs Boson

- In the SM, there is one Higgs doublet and a spin-0 particle: the Higgs boson (H).

It can be produced at colliders:



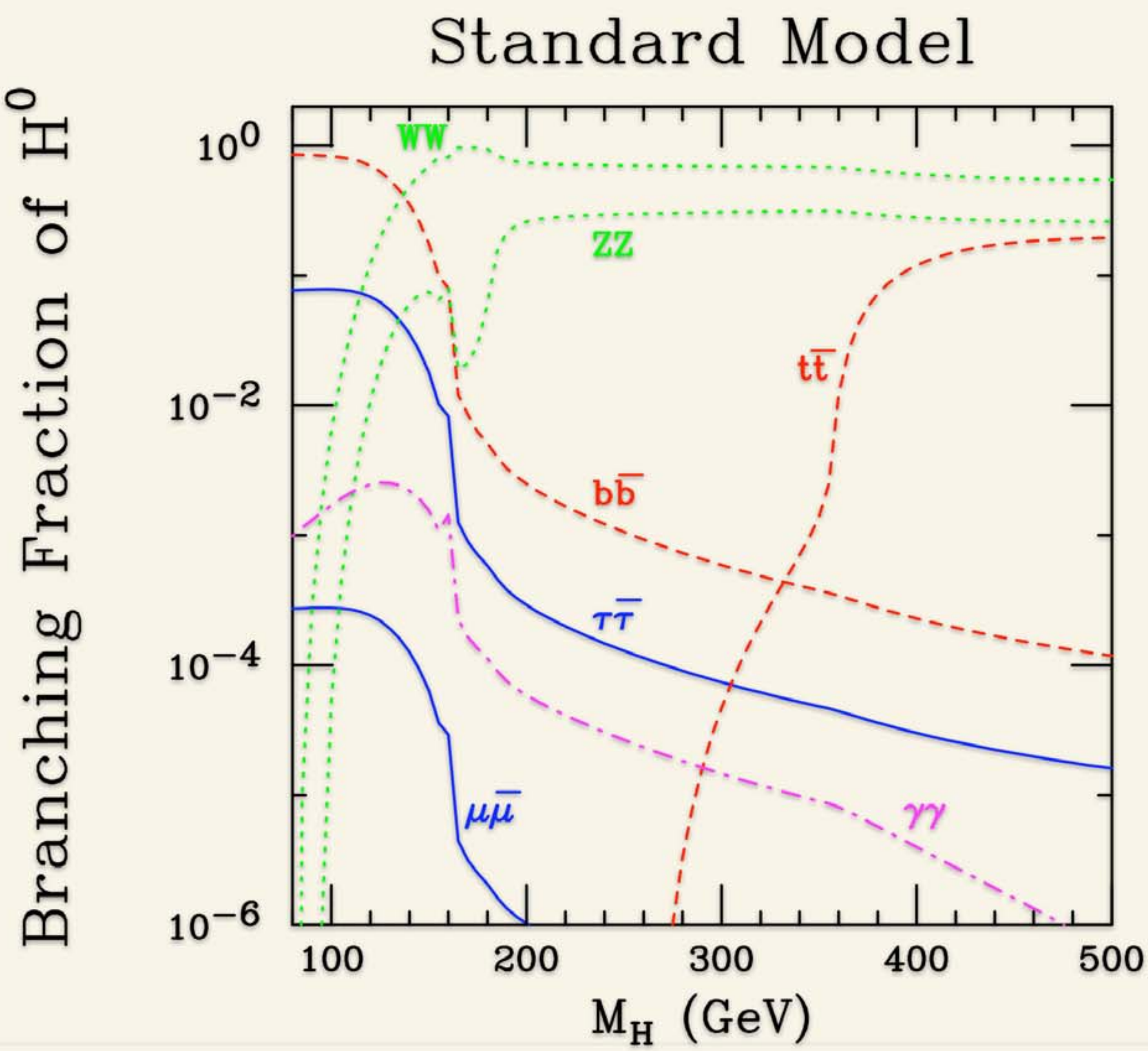
Its decays are well known:



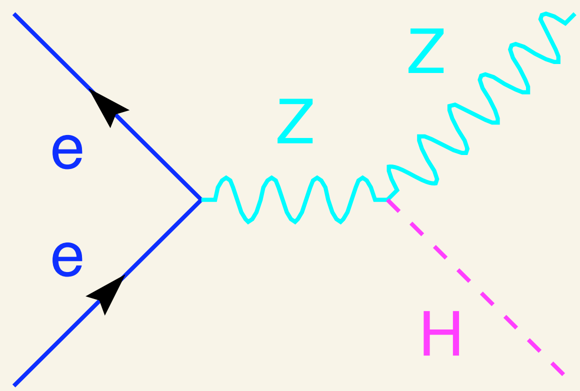
Why has't it been discovered yet?

We need higher energy and higher luminosity!

Branching Fractions of the Higgs Boson

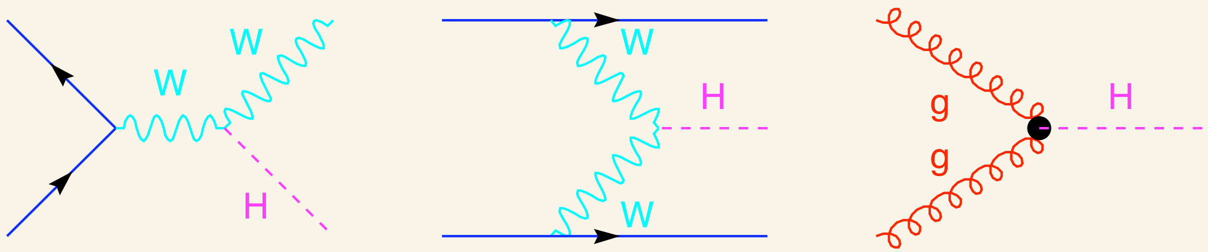


The Search for the SM Higgs boson



- Mass limit from LEP 2
  With a CM energy up to $\sqrt{s} = 209\,\mathrm{GeV}$
  and L = 100 pb^{-1} per experiment,
  a stringent mass limit for the Higgs boson
  at 95% C.L. is $M_H > 114$ GeV/c^2

Discovery potential of hadron colliders

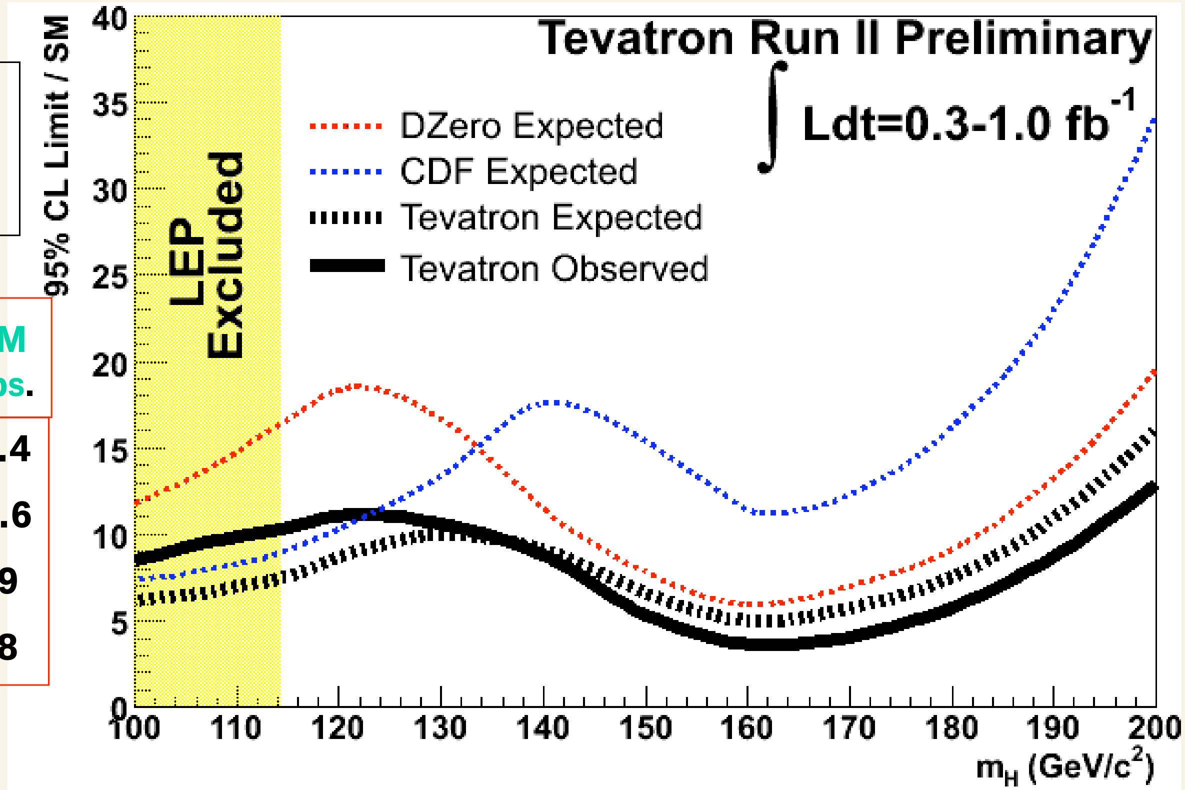


- The Tevatron Run II will be able to discover a SM Higgs boson up to 190 GeV with 30 fb^{-1}, or it will exclude the Higgs boson at 95% C.L. with 10 fb^{-1}.
- The LHC will be able to observe a SM Higgs boson with a mass up to approximately 1 TeV.

Stange, Marciano, and Willenbrok (1994); Han and Zhang (1998). CMS Technical Proposal (1994); ATLAS Technical Proposal (1994); ATLAS Technical Design Report (1999).

Tevatron SM Higgs Combination

All CDF and DØ results now combined for the first time ➔

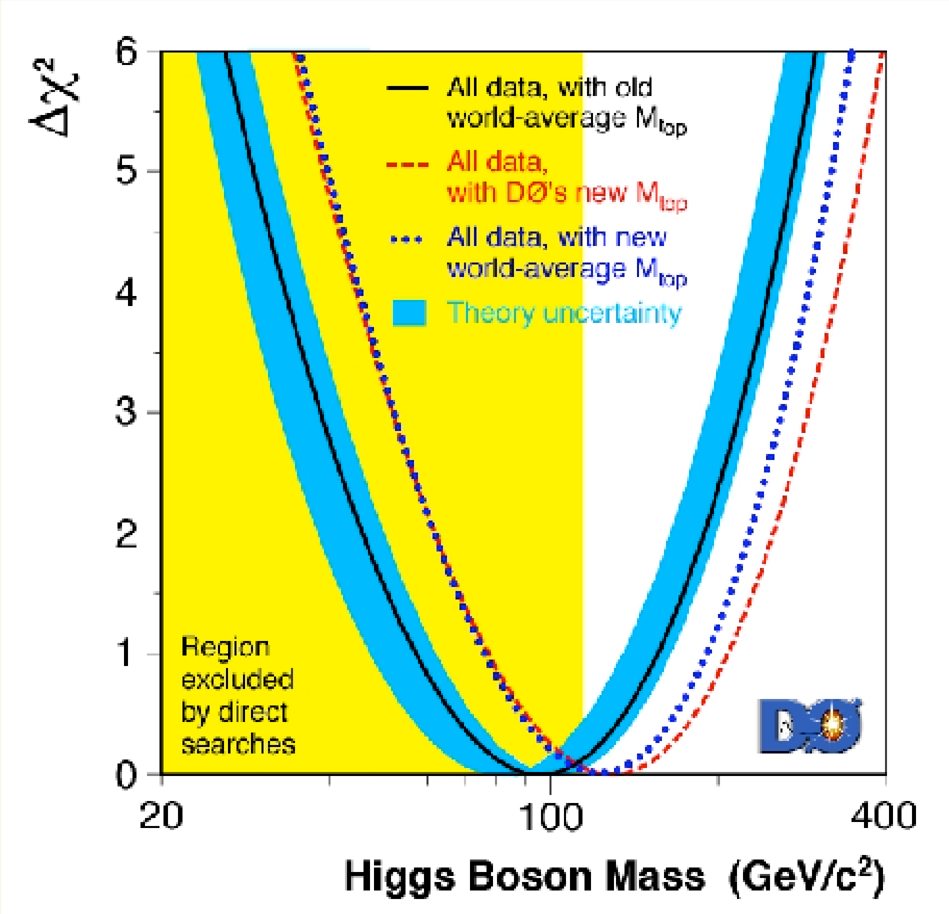


m_H (GeV)	Limit / SM Exp.	Obs.
115	7.6	10.4
130	10.1	10.6
160	5.0	3.9
180	7.5	5.8

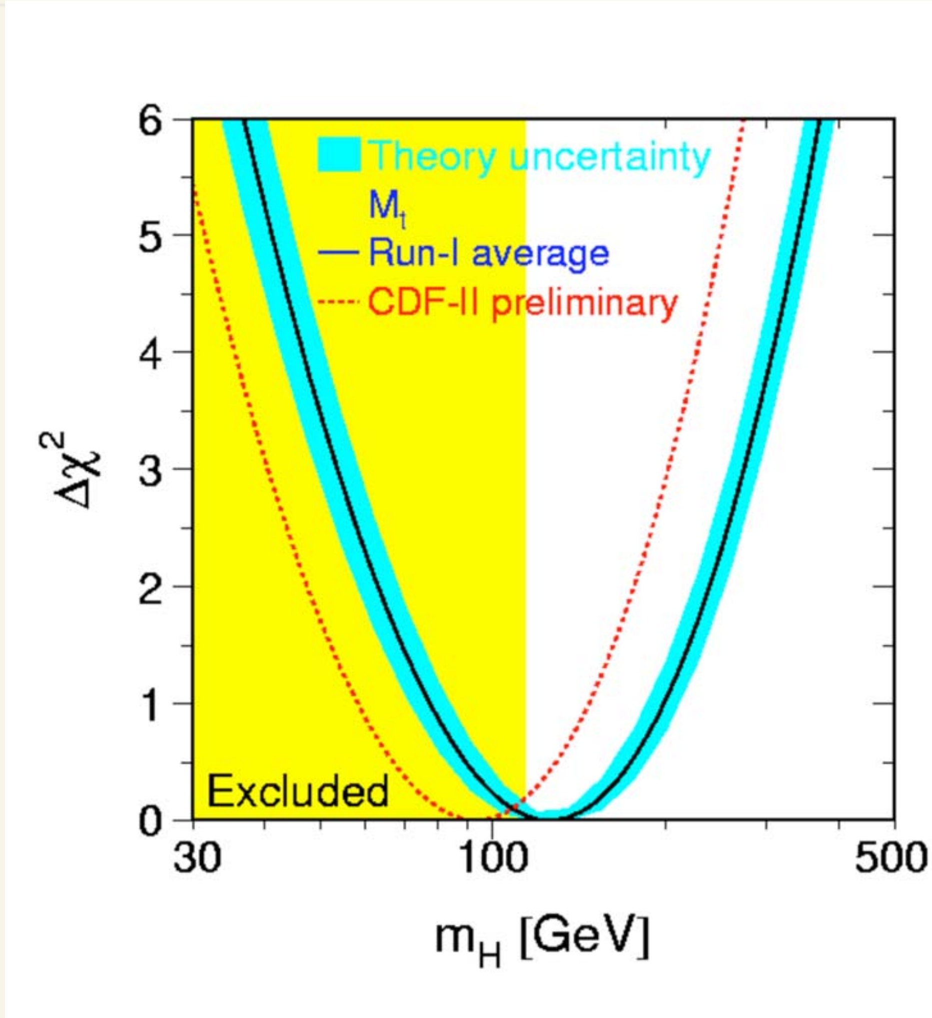
Note: the combined result is essentially equivalent to one experiment with 1.3 fb^{-1}, since both experiments have "complementary" statistics at low and high mass

➔ we are indeed already close to the sensitivity required to exclude or "evidence" the higgs at the Tevatron

Implications of Electroweak Precision Data for Higgs Mass with New m_t

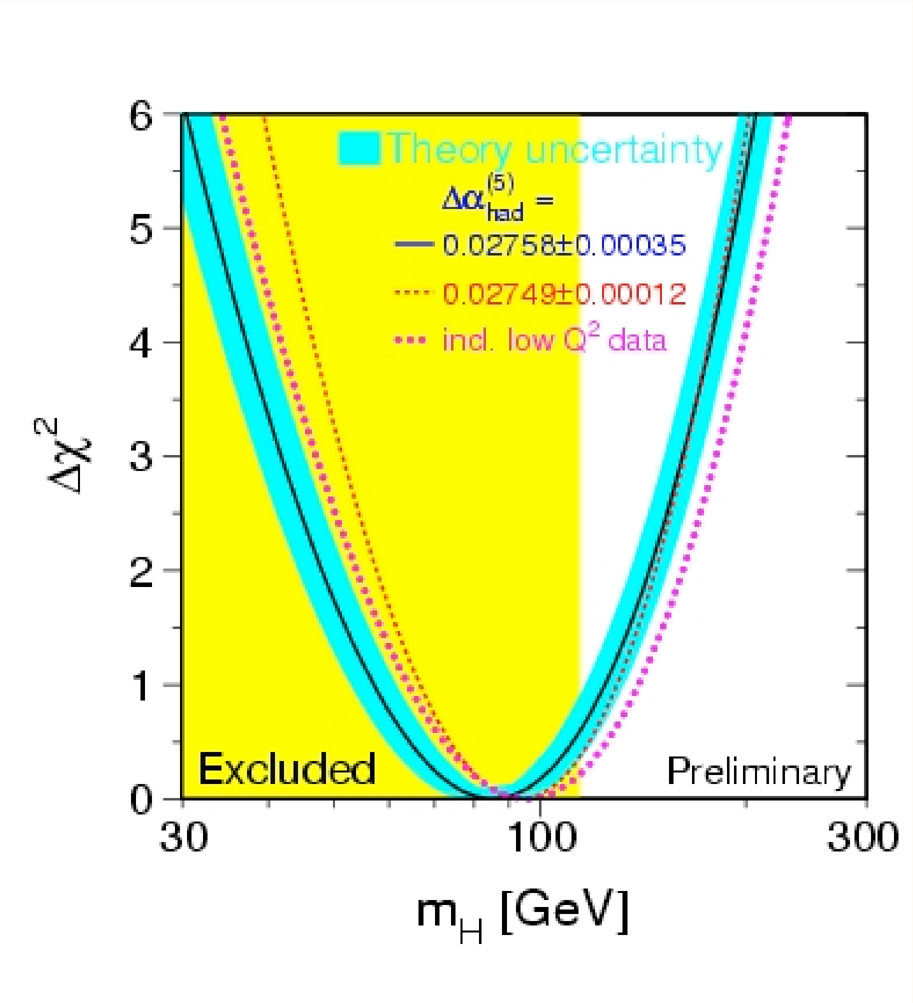


M.W. Grunewald (2003); The D0 Collaboration (2004)



m_{top}=173.5 +2.7–2.6(stat) ±3.0(syst) GeV/c2

The CDF Collaboration (2005).



m_{top}= 171.4 ± 1.2 ± 1.8 GeV/c2

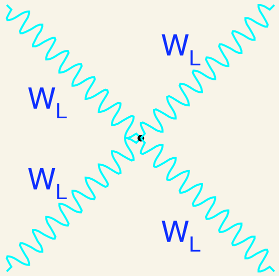
The CDF and the D0 Collaborations, hep-ex/0608032.

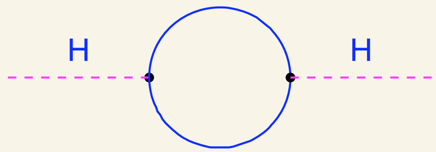
Problems in the SM Higgs Sector

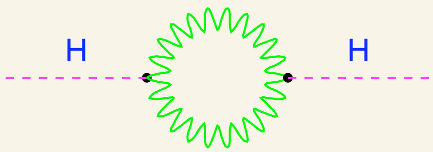
Requiring unitarity, we must have $M_H \leq 1$ TeV.

If $M_H \geq 1$TeV, WW scattering will become strong.

Quadratic divergence: M_H naturally of order M_{Planck}.

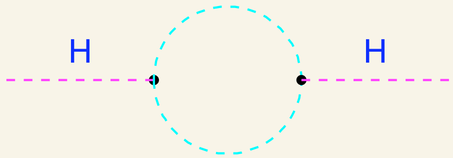


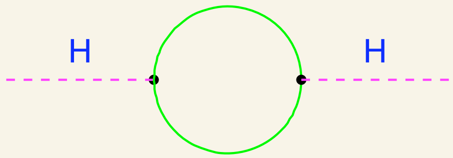




One good way out:

A low energy fermion-boson supersymmetry.





The Minimal Supersymmetric Model

- In the minimal supersymmetric standard mode (MSSM), there are two Higgs doublets with vacuum expectation value (VEVs) v_1 and v_2, and five Higgs bosons: two scalars H^0 and h^0, one pseudoscalar A^0, and a pair of singly charged Higgs bosons $H^{\pm}$.
- At the tree level, $m_h \leq M_Z$ 91 GeV $< m_H$, with radiative corrections, m_h can be in the range 125 GeV $\leq m_h \leq$ 135 GeV.
- There are only two free parameters in the Higgs sector, often chosen to be m_A and $\tan\beta \equiv v_2/v_1$.

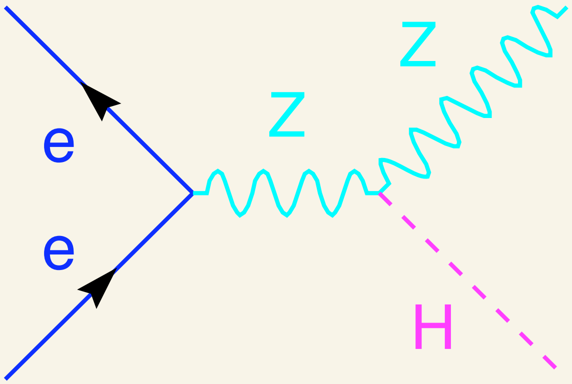
Mass limit from LEP 2

There are two complementary processes:

$e^+e^- \rightarrow Zh^0 \quad \propto \sin^2(\beta-\alpha)$

and

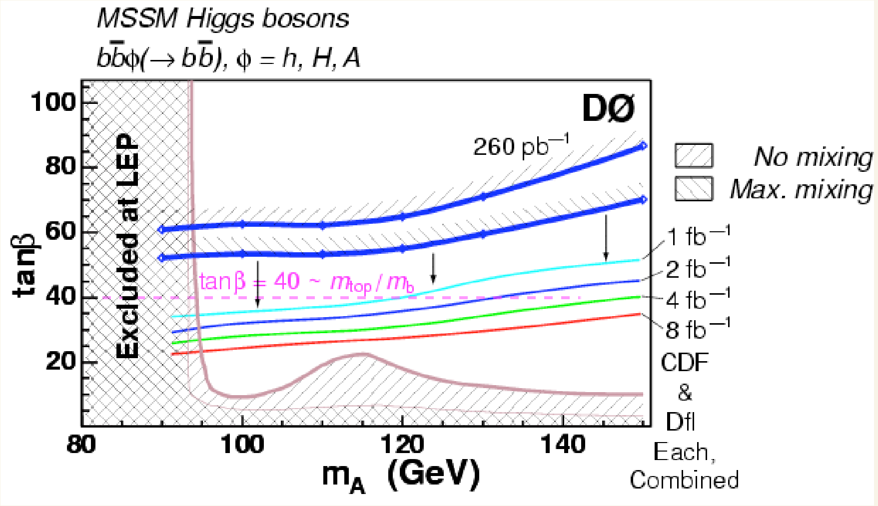
$e^+e^- \rightarrow h^0A^0 \propto \cos^2(\beta-\alpha)$

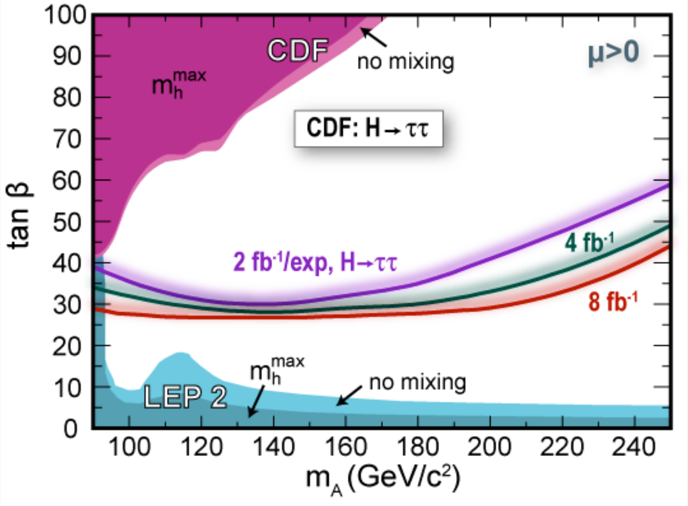


- With a CM energy up to $\sqrt{s} = 209\,\mathrm{GeV}$ and L = 100 pb^{-1} per experiment, the Higgs mass reach at 95% C.L. is MSSM: $M_h, M_A > 91$ GeV/c^2

Conclusions

- The MSSM provides the TeVatron with a real shot at a Higgs discovery
  - Light h^0, decent xsec
  - Decays to b, τ
- Null results for ϕ^0 searches put the squeeze on the MSSM from the large tan β side





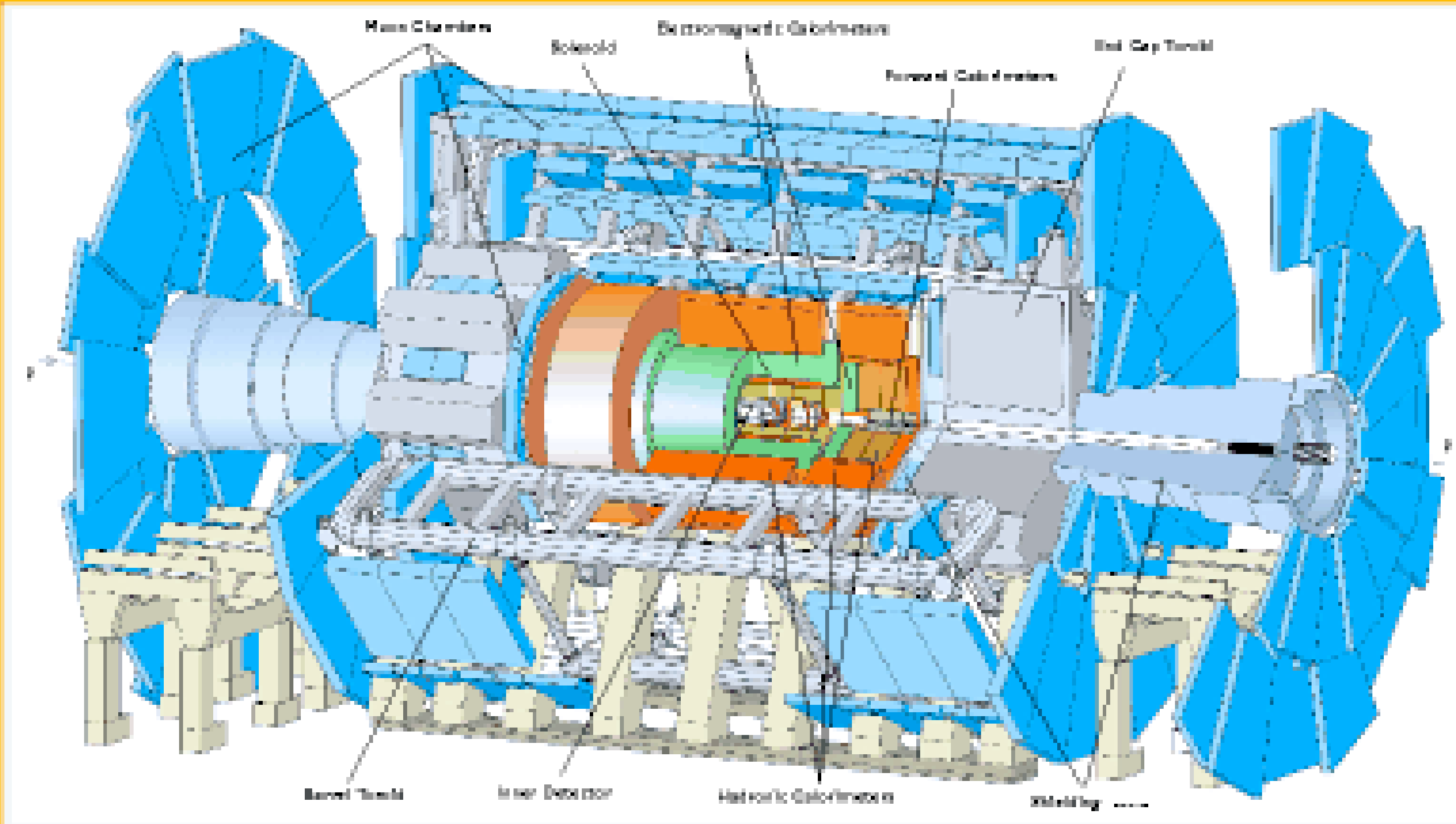
Andy Hocker, ICHEP06, Moscow

The Search for New Particles at Hadron Colliders

- We need accelerators: Fermilab Tevatron Collider near Chicago and CERN Large Hadron Collider (LHC) in Geneva.
- We need detectors: D0 and CDF (Tevatron), as well as ATLAS and CMS (LHC).
- We look for e, μ, γ (photon), jets, and hadrons (mesons or baryons).
- A jet = a quark, an anti-quark, or a gluon.

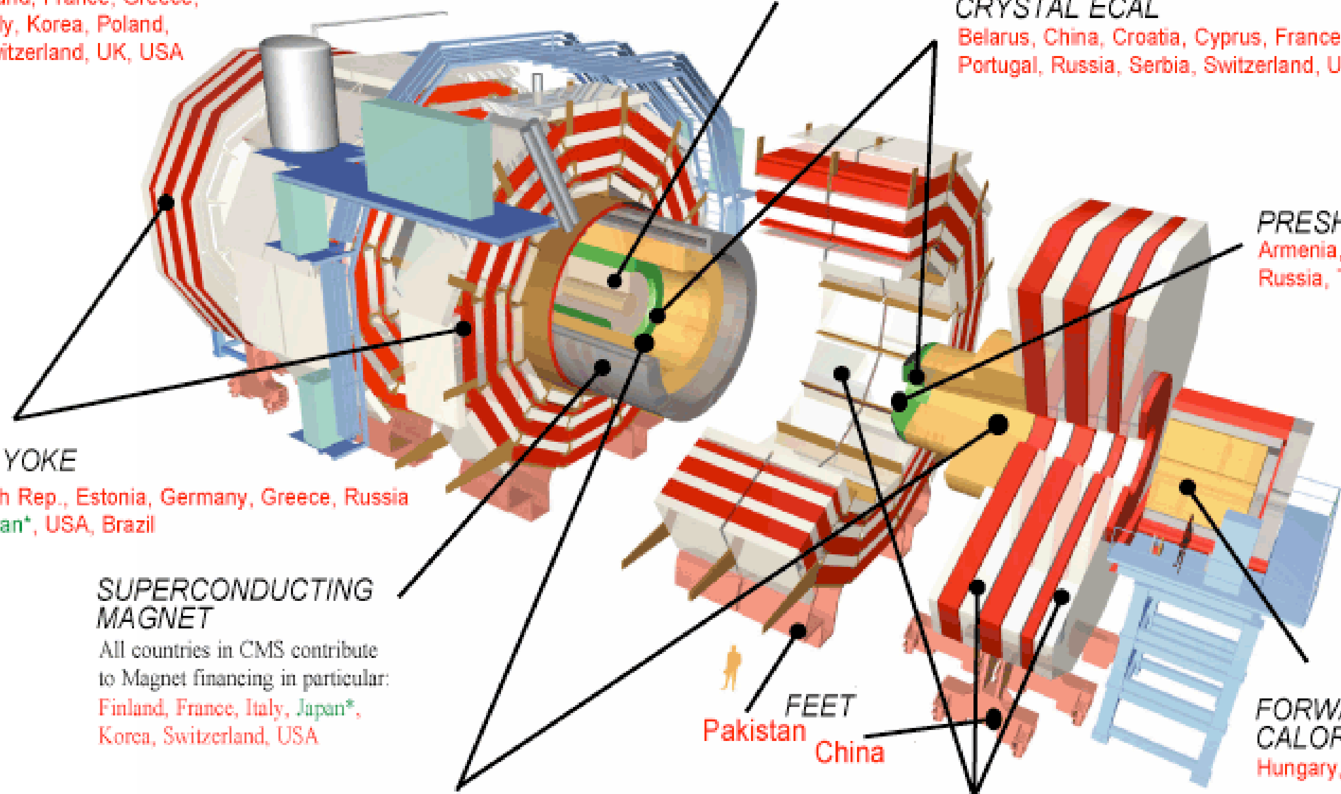
ATLAS

A Toroidal LHC ApparatuS



CMS Collaboration

36 Nations, 159 Institutions, 1940 Scientists (February 2003)



Total weight	: 12500 T
Overall diameter	: 15.0 m
Overall length	: 21.5 m
Magnetic field	: 4 Tesla

High Energy Frontier in HEP

M. Lamont
Tev4LHC meeting
@ CERN (April)

Next projects on the HEP roadmap

- Large Hadron Collider LHC at CERN: pp @ 14 TeV
  - LHC will be closed and set up for beam on 1 July 2007
  - First beam in machine: August 2007
  - First collisions expected in November 2007
  - Followed by a short pilot run
  - First physics run in 2008 (starting April/May; a few fb^{-1}?)
- Linear Collider (ILC) : e+e- @ 0.5-1 TeV
  - Strong world-wide effort to start construction earliest around 2009/2010, if approved and budget established
  - Turn on earliest 2015 (in the best of worlds)
  - Study groups in Europe, Americas and Asia (→World Wide Study)

Quest for the Higgs particle is a major motivation for these new machines

Production of Higgs Bosons

A. Gluon Fusion: $gg \to \phi^0$

B. Bottom Quark Fusion: $b\bar{b} \to \phi^0$

- $\sigma(gg \to \phi^0 b\bar{b})[m_b(M_b)]$
  $\approx 3\sigma(gg \to \phi^0 b\bar{b})[m_b(M_\phi)],\ M_\phi = 200$ GeV
- $\sigma(gg \to \phi^0 b\bar{b}) \approx \sigma(b\bar{b} \to \phi^0),\ \mu_F = M_\phi/4$

V. Ravindran, J. Smith, and W.L. van Neerven (2003); R.V. Harlander & W.B. Kilgore (2002); C. Anastasiou & K. Melnikov (2002).
M. Spira, A. Djouadi, D. Graudenz, P.M. Zerwas (1995).
T. Plehn (2002); F. Maltoni, Z. Sullivan and S. Willenbrock (2003);
E. Boos and T. Plehn (2003); R.V. Harlander and W.B. Kilgore (2003).
B. Plumper, DESY-THESIS-2002-005.
J. Campbell et al., Les Houches (2003), arXiv:hep-ph/0405302.

Order Counting for Bottom Quark Fusion

Dicus, Stelzer, Sullivan and Willenbrock (1999)

Leading-order contribution: $b\bar{b} \to H$: $\mathcal{O}[\alpha_s^2 \ln^2(M_H/m_b)]$

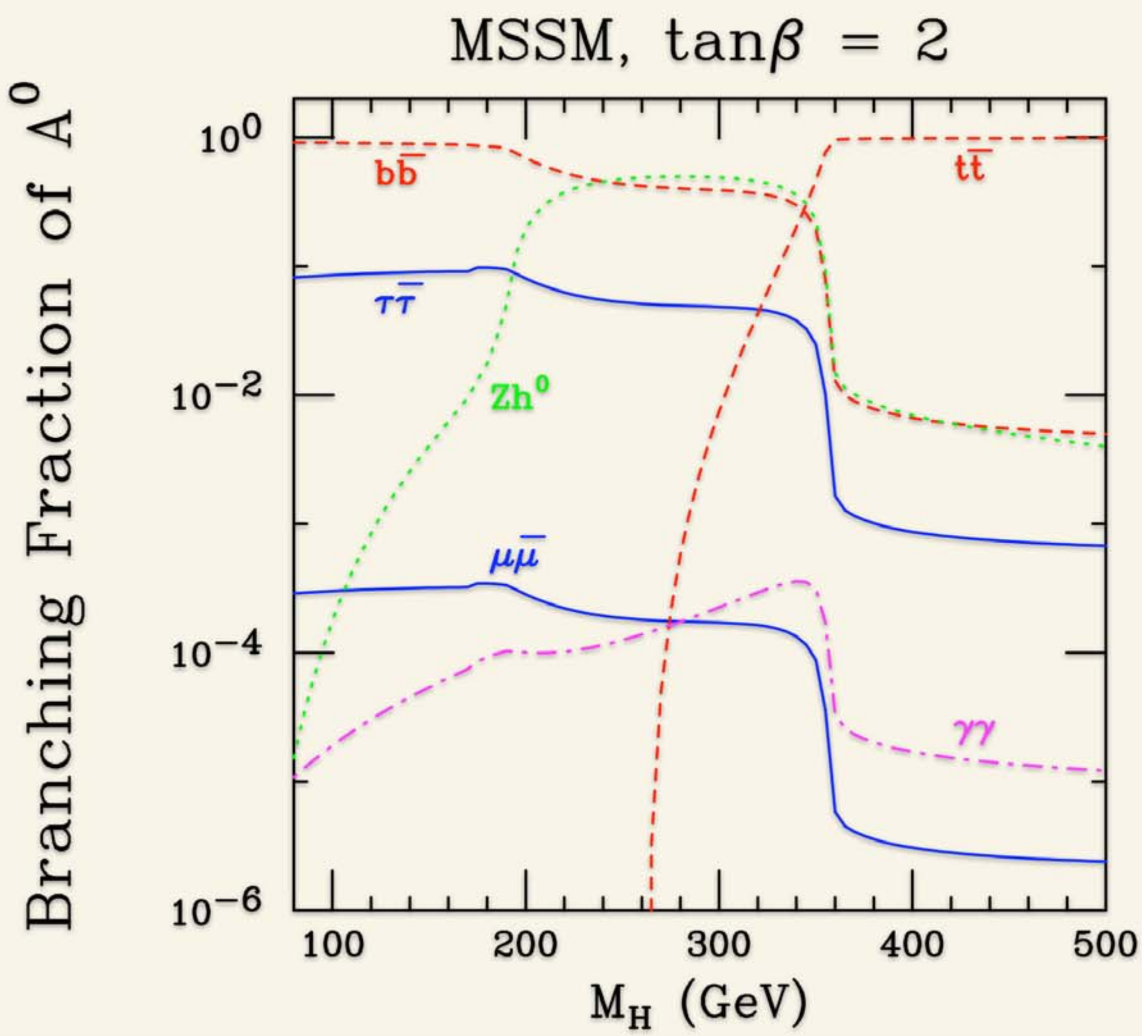
$\mathcal{O}(\alpha_s)$ correction:
(1) $b\bar{b} \to H$ with virtual gluon, and
(2) $b\bar{b} \to Hg$: soft, hard/collinear, and hard/non-colinear

$\mathcal{O}[(1/\ln(M_H/m_b)]$ correction: $bg \to bH$

$\mathcal{O}[1/\ln^2(M_H/m_b)]$ corrections: $gg \to b\bar{b}H$

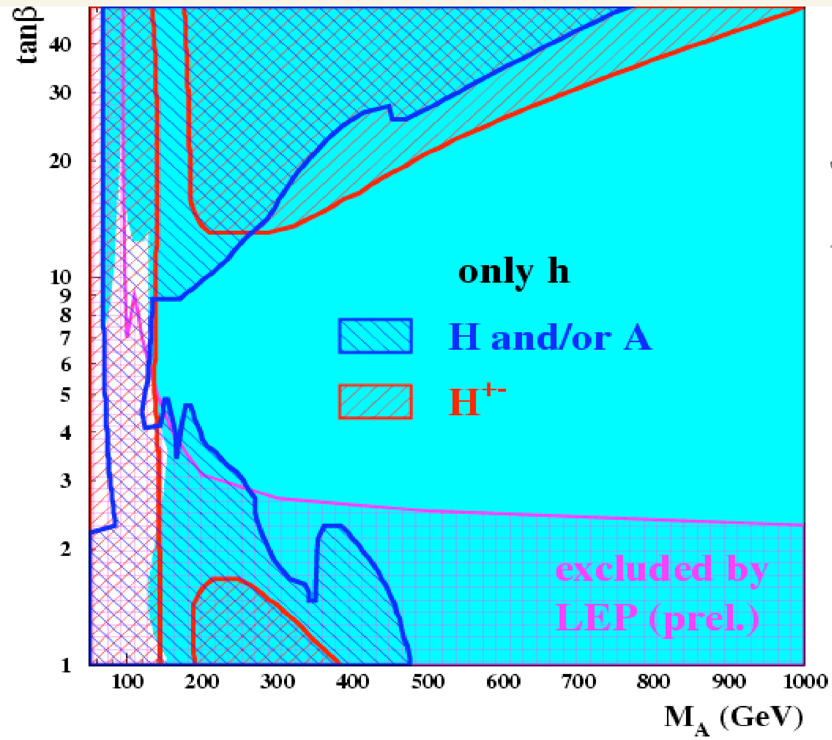
Next-to-leading order (NLO) correction =
$\mathcal{O}(\alpha_s)$ correction $+\mathcal{O}[(1/\ln(M_H/m_b)]$ correction.

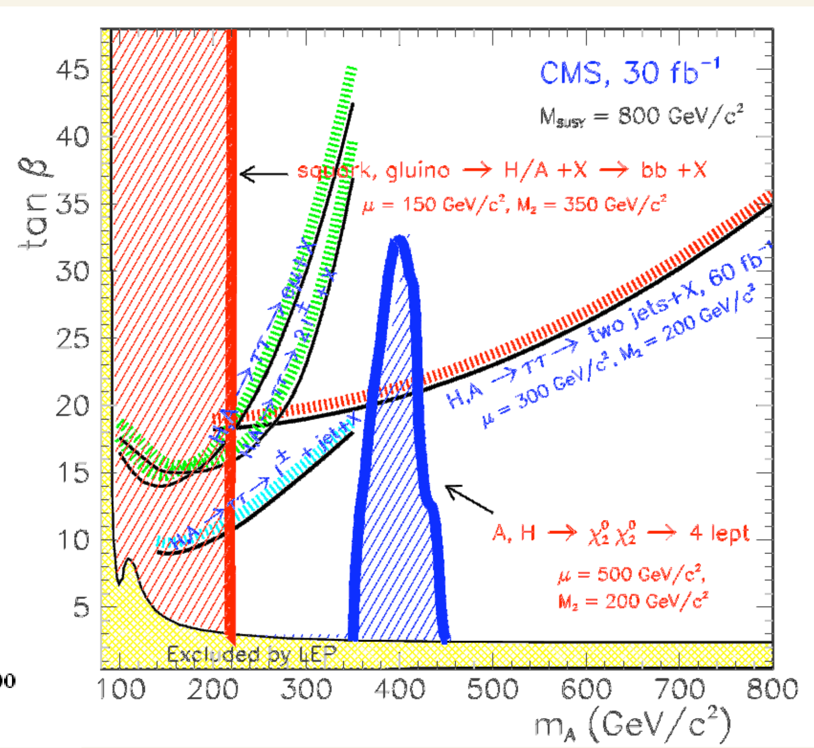
The Higgs Pseudoscalar (A^0)



- A/H → ττ
- A/H → μμ
- A/H → bb/ μμ in bb H/A

- A, H → $\chi_2^0 \chi_2^0$ → $4l$ + E_T^{miss}
- A, H in cascade decays of sparticles





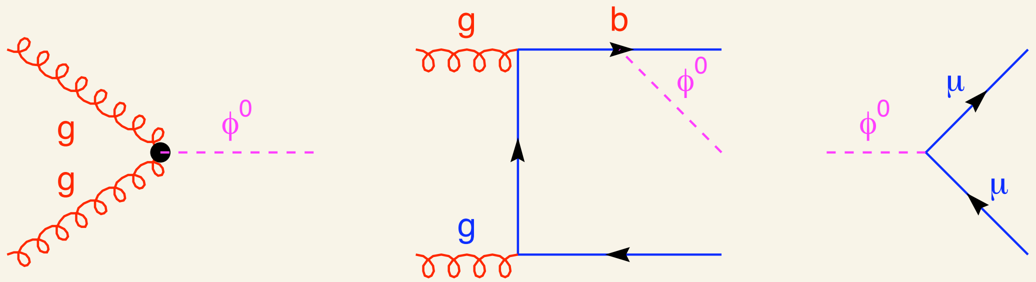
Albert De Roeck, CERN
SUSY 2005

B(A^0 to X_2 X_2)

- tan(b) = 3,
  M_A = 336 GeV, M_H = 343 GeV, M_X = 117 GeV
- A^0 to b bB 0.095
- A^0 to X_2 X_2 0.165

- tan(b) = 20,
  M_A = 292.8 GeV, M_H = 294.7 GeV, M_X = 138 GeV
- A^0 to b bB 0.775
- A^0 to X_2 X_2 0.030

Discovering the Higgs Bosons with Muons



- The A^0 and the H^0 might be observable in a large region of parameter space with $\tan\beta \geq 10$.
- This discovery channel of $\mu^+\mu^-$ will allow precise reconstruction for the Higgs boson masses.
- Kao and Stepanov (1995);
  Barger and Kao (1998);
  Dawson, Dicus and Kao, Phys. Lett. **B545**, 132 (2002).

Cross Section in the MSSM

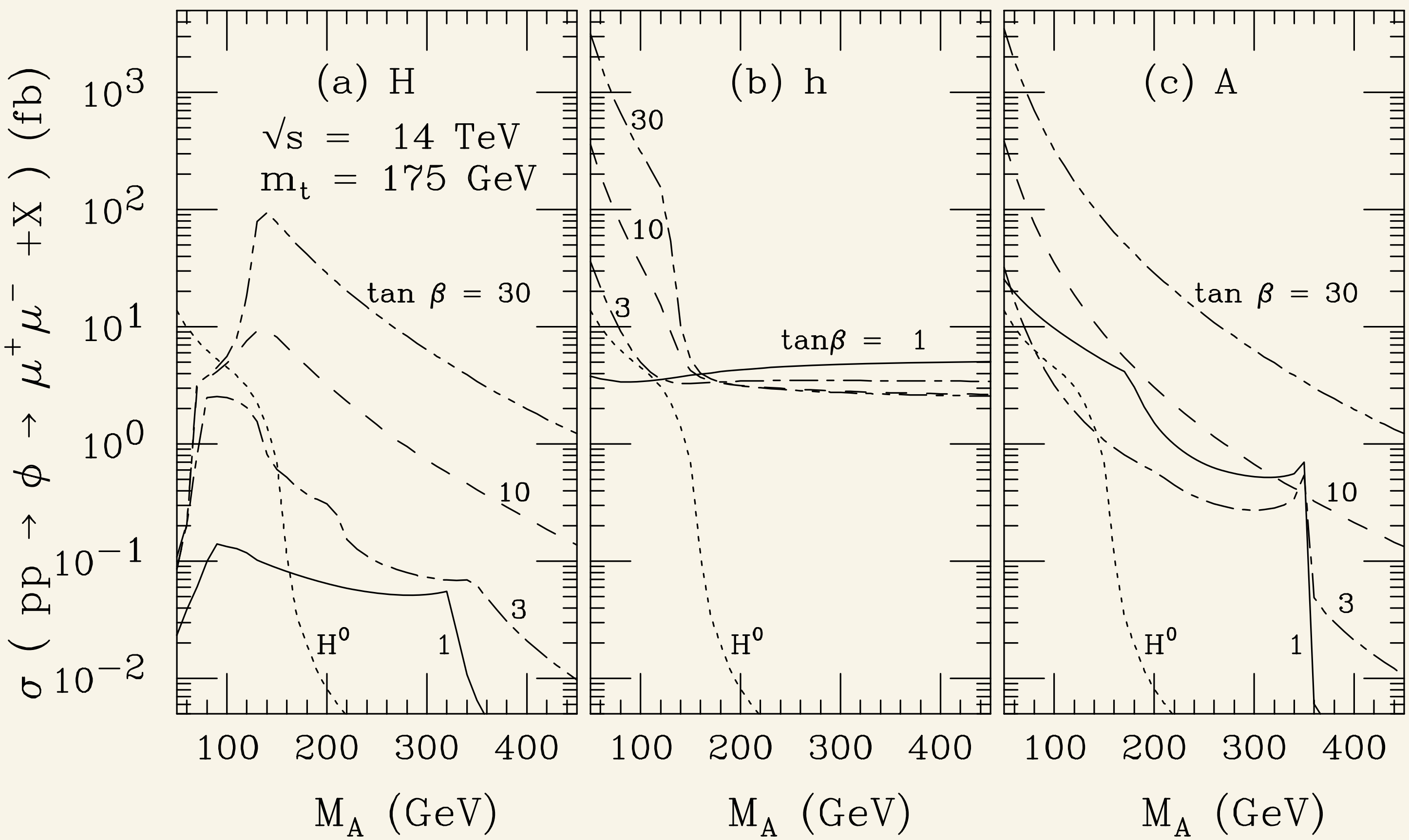
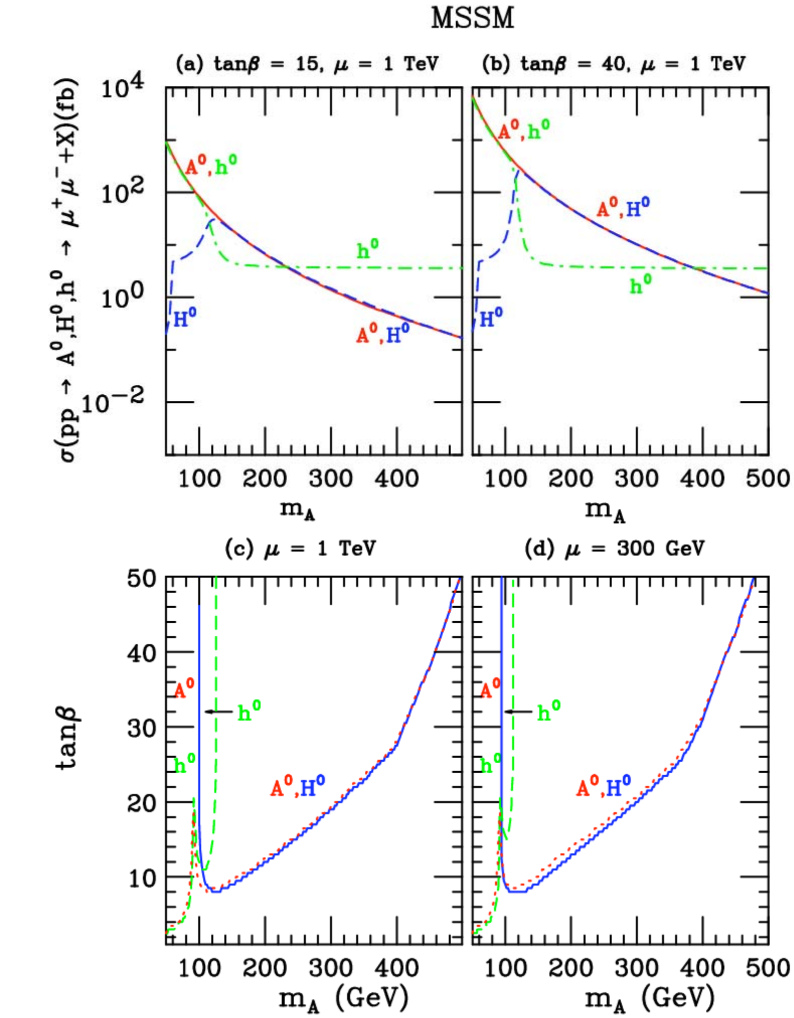
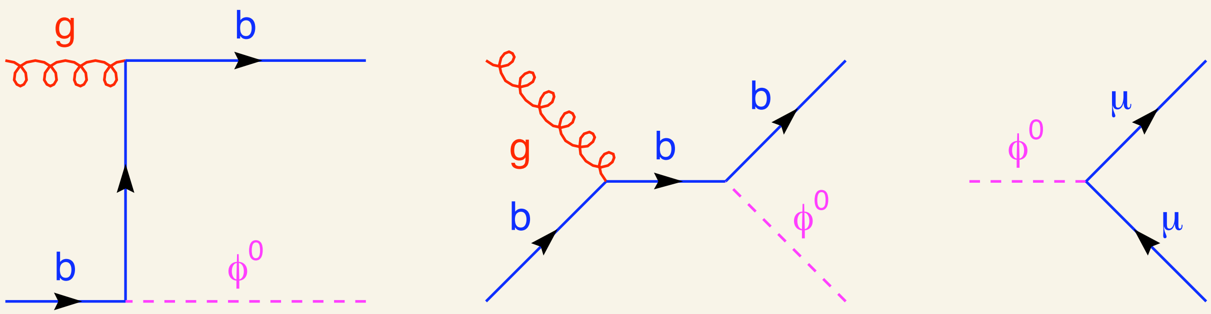


FIG 1/Kao and Stepanov

Minimal Supersummetry



Discovering Higgs Bosons with Muons and a Bottom Quark



S. Dawson, D. Dicus, C. Kao and R. Malhotra, Phys. Rev. Lett. 92, 241801 (2004). S. Dawson, D. Dicus, and C. Kao, Phys. Lett. B **545**, 132 (2002);
V. Barger and C. Kao, Phys. Lett. B **424**, 69 (1998);
C. Kao and N. Stepanov, Phys. Rev. D **52,** 5025 (1995).

The Physics Backgrounds

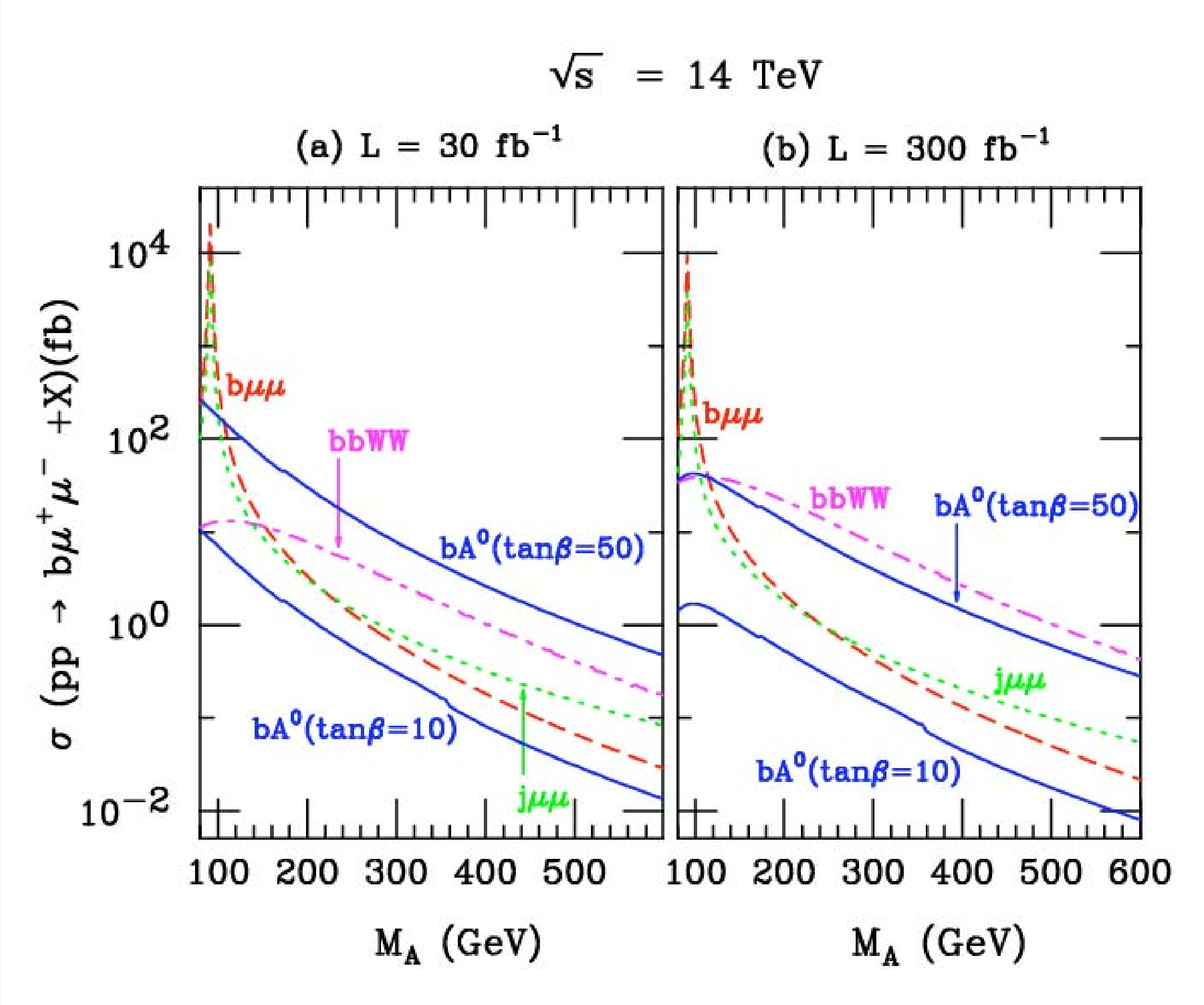
- For the associated final state of $b\phi^0 \to b\mu^+\mu^-$, the dominant physics background comes from $pp \to b\,\mu^+\mu^- + X$, and $pp \to b\bar{b}\,W^+W^- \to b\bar{b}\,\mu^+\mu^- + \not{E}_T$
- Additional contributions come from the production of $j\mu^+\mu^-$, $j = g, u, d, s$, and c.
- We take the b tagging efficiency to be $\varepsilon_b = 0.6$ ($LL = 30\ \mathrm{fb}^{-1}$) or 0.5 ($HL = 300\ \mathrm{fb}^{-1}$), $\varepsilon_c = 0.1$ = probability of c misidentified as b, $\varepsilon_j = 0.01$ = probability of jets mistagged as b.

•ATLAS Technical Design Report (1999).

The Acceptance Cuts

We have applied realistic acceptance cuts proposed for each event at the LHC as follows.

- (a) We require 2 isolated muons with
  $p_T(\mu) > 20$ GeV, and $|\eta(\mu)| < 2.5$.
- (b) All jets are required to have
  $p_T(j) > 15$ GeV (LL) or 30 GeV (HL)
  and $|\eta(j)| < 2.5$.
- (c) To reduce the background from $b\bar{b}WW$ ($t\bar{t}$),
  we require $\not{E}_T < 20$ GeV (LL) or 40 GeV (HL).

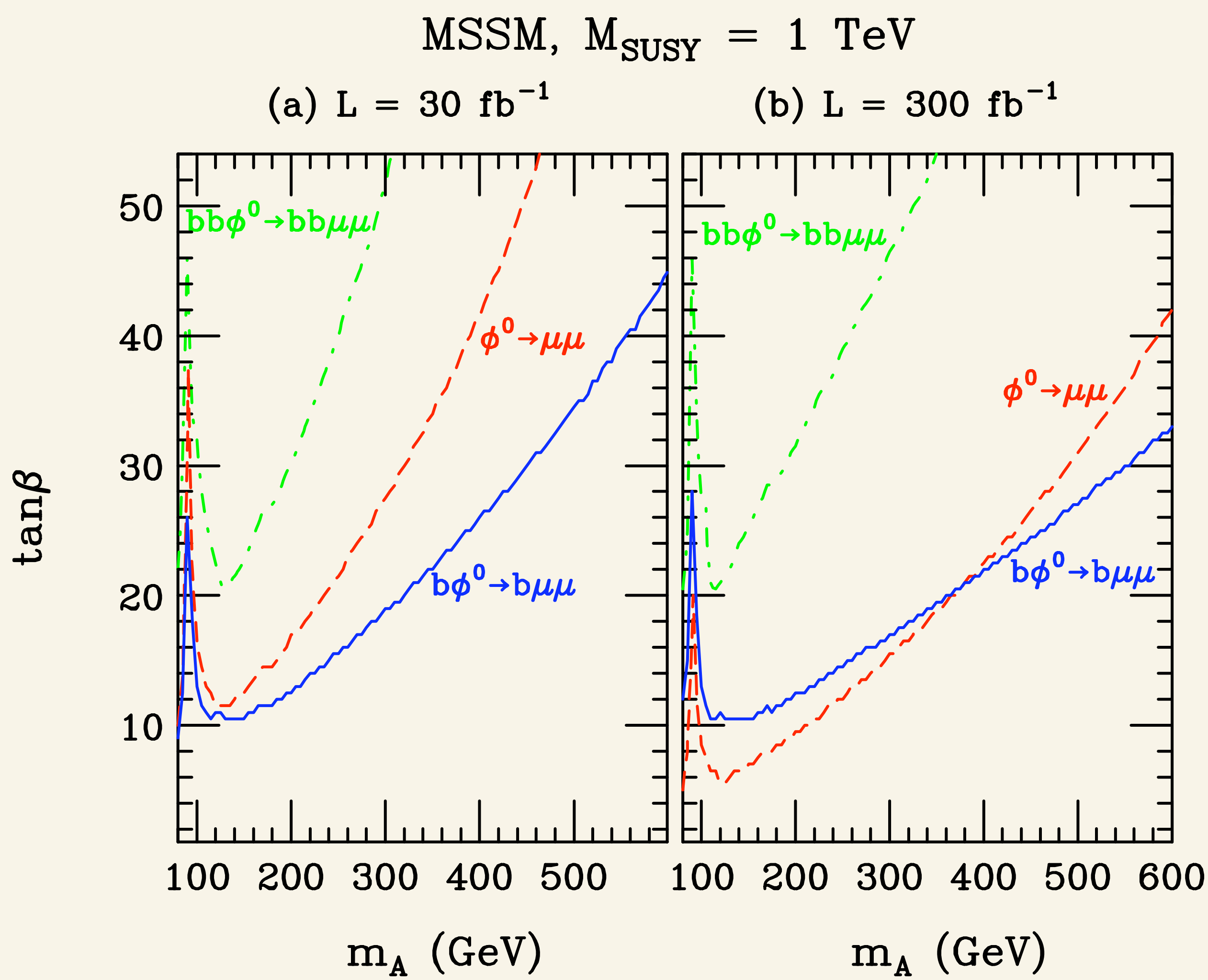


S. Dawson, D. Dicus, C. Kao and R. Malhotra (2004)

The Discovery Potential

- To study the discovery potential of
  $$pp \to b\,\phi^0 \to b\,\mu^+\mu^- + X$$
  we calculate the SM background from
  $pp \to b\,\mu^+\mu^- + X$
  and
  $pp \to b\bar{b}W^+W^- \to b\bar{b}\,\mu^+\mu^- + X$
  in the mass window of $m_\phi \pm \Delta M_{\mu\mu}$.
- $\Delta M_{\mu\mu} = 1.64\,[(\Gamma_\phi/2.36)^2 + \sigma_m^{\,2}]^{1/2}$,
- Γ_ϕ is the width of the Higgs boson, and
- σ_m = the muon mass resolution $\cong 0.02\, m_\phi$.

Discovery Potential at the LHC

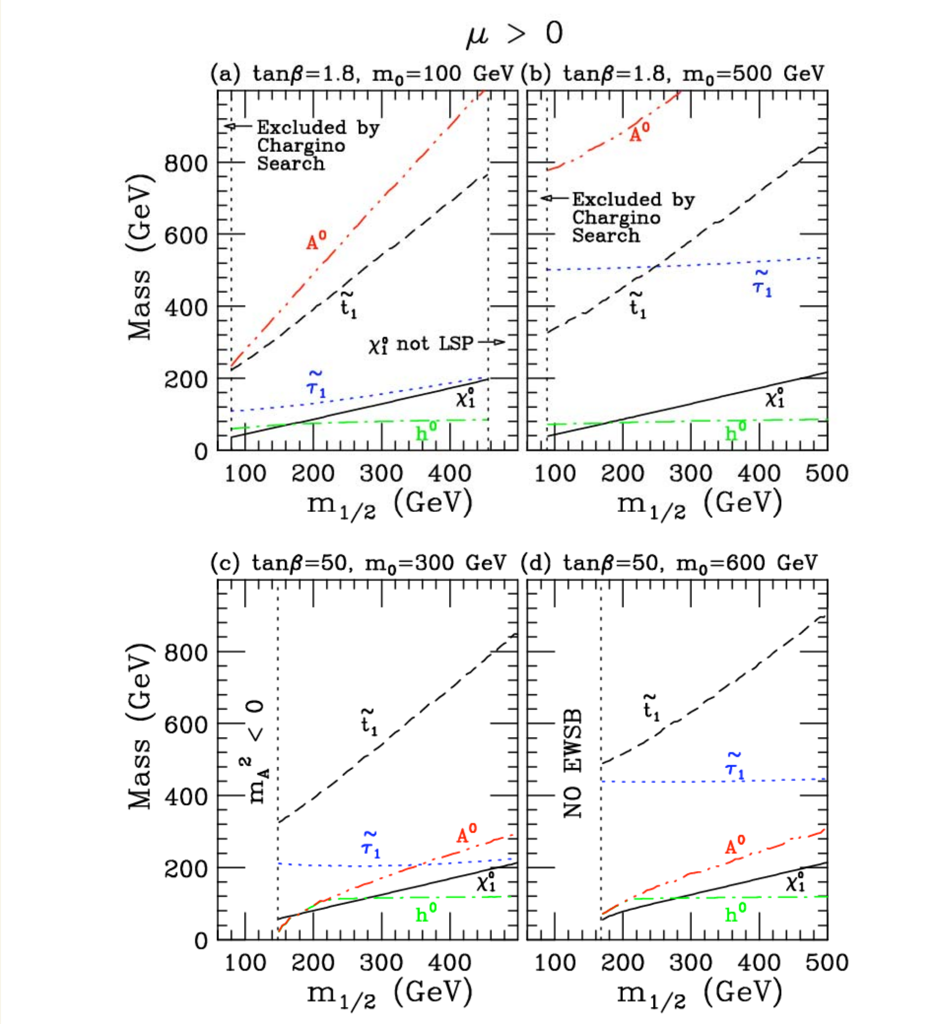


Summary for Higgs Decay into Muons

- The discovery channel of $b\phi^0 \to b\mu^+\mu^-$ offers great promise to discover the A^0 and the H^0 at the LHC for $\tan\beta > 10$, $m_A < 650$ GeV with $L = 30\ \text{fb}^{-1}$.
- A higher luminosity of $300\ \text{fb}^{-1}$ can improve the discovery reach in m_A up to $m_A = 800$ GeV.
- The $b\phi^0$ channel greatly improves the discovery potential beyond the reach of the inclusive channel $pp \to \phi^0 \to \mu^+\mu^- + X$.
- This discovery channel might provide good opportunities to measure important parameters such as the Higgs masses, $\tan\beta$, and Higgs couplings with bottom quarks and leptons.

The Minimal Supergravity Model

- In the minimal supergravity unified model (mSUGRA), it is assumed that SUSY is broken in a hidden sector with SUSY breaking communicated to the observable sector through gravitational interactions, leading to a common scalar mass (m_0), a common gaugino mass ($m_{1/2}$), a common trilinear coupling (A_0), and a bilinear coupling (B_0) at the grand unified scale (M_{GUT}).
- We often choose $m_0, m_{1/2}, A_0, \tan\beta,$ and $\mathrm{sign}(\mu)$ as the 5 free parameters.
- The masses and couplings of SUSY particles are evaluated with renormalization group equations.



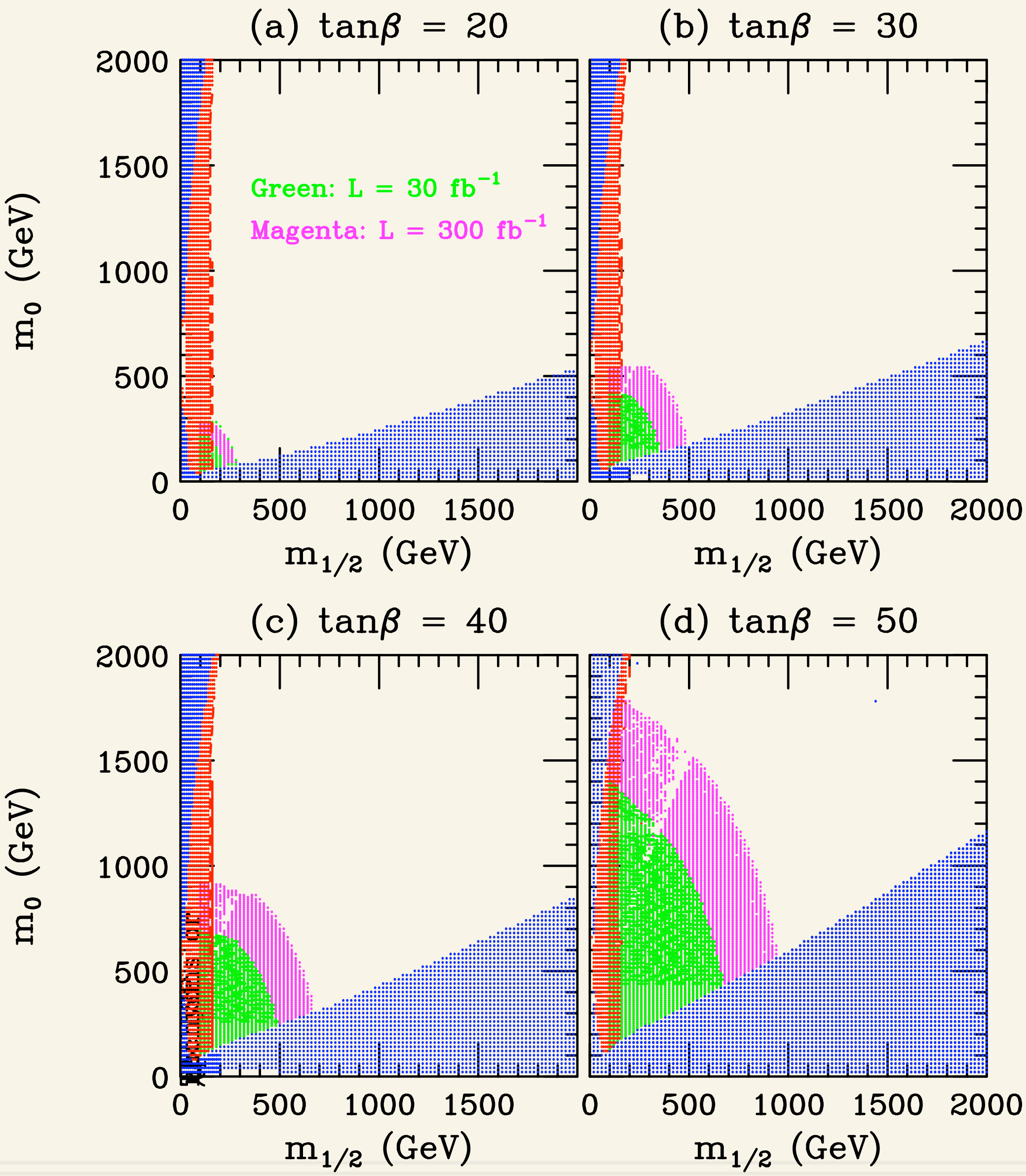
Barger and Kao (1998)

Higgs bosons of minimal supergravity

In addition to m_0 and $m_{1/2}$, $\tan\beta$ is a very important parameter:

- an increase in $\tan\beta$ leads to a larger m_h but a reduction in m_A and m_H;
- for $\tan\beta \sim 2$, m_A is usually large and the cross section of a Higgs signal for H^0 or A^0 is often much smaller than that of the background;
- for $\tan\beta \geq 35$, the cross section of the Higgs signal is greatly enhanced and can become slightly larger than the background.

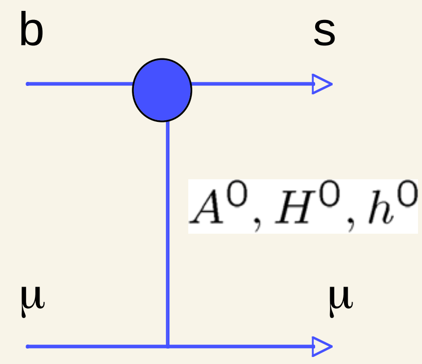
Minimal Supergravity Model



$B_s \to \mu^+\mu^-$

- This rare decay has a small branching fraction in the Standard Model
  $$\mathrm{B}(B_s \to \mu^+\mu^-) = 3.4 \times 10^{-9}$$
- The current experimental upper limit from CDF and D0 is
  $$\mathrm{B}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-7}$$

$B_s \to \mu\mu$ and SUSY



$$B(B_s \to \mu^+\mu^-) \sim 5 \times 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300\mathrm{GeV}}{M_A}\right)^4$$

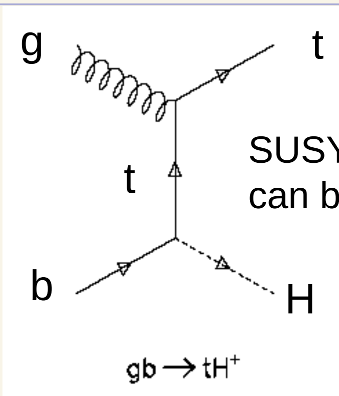
The discovery region of a neutral Higgs boson through
pp -> bH -> b mu mu
at LHC and the discovery region of
Bs -> mu mu
at Tevatron and LHC overlap.
C. Kao and Y. Wang (2006)

Y Okada (ICHEP 2006)

Comparison with the charged Higgs boson production at LHC

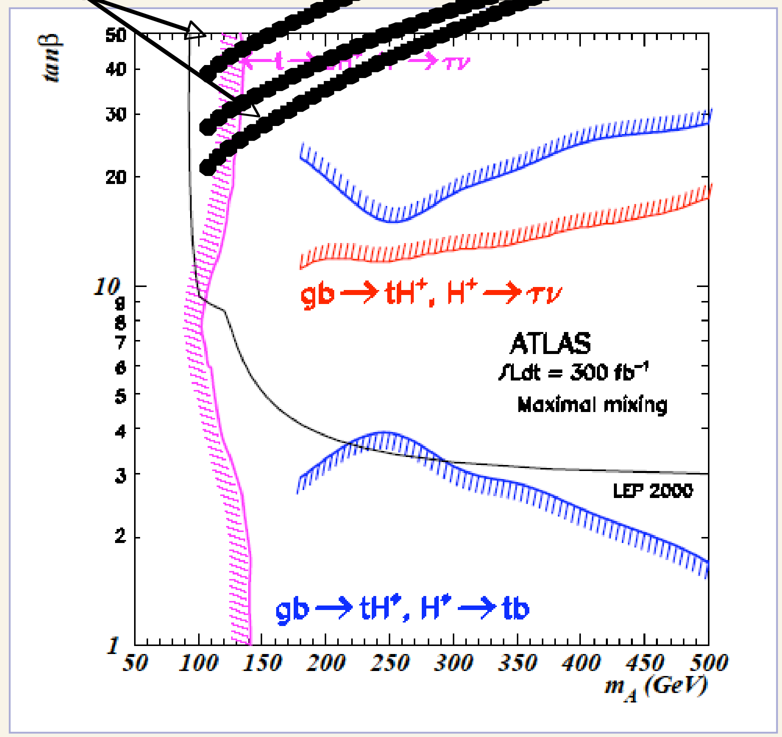
- The parameter region covered by B decays and the charged Higgs production overlaps.
- If both experiments find positive effects, we can perform Universality Test of the charged Higgs couplings.

B->τν:	H-b-u coupling
B->Dτν :	H-b-c coupling
gb->tH:	H-b-t coupling



SUSY loop vertex correction can break the universality.

Belle B->τν: excluded region (95.5%CL)



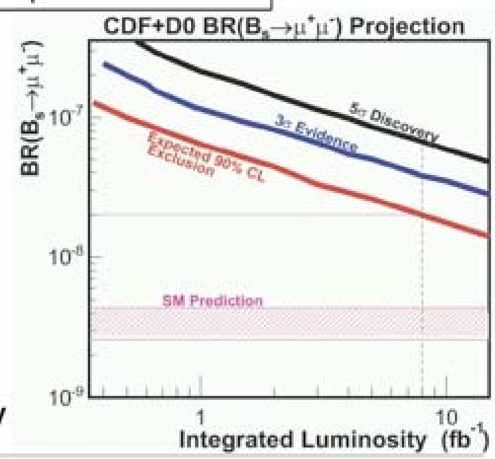
K.A.Assamagan, Y.Coadou, A.Deandrea

State-of-the-art (before ICHEP06)

- All decay channels beyond the reach of experiments:

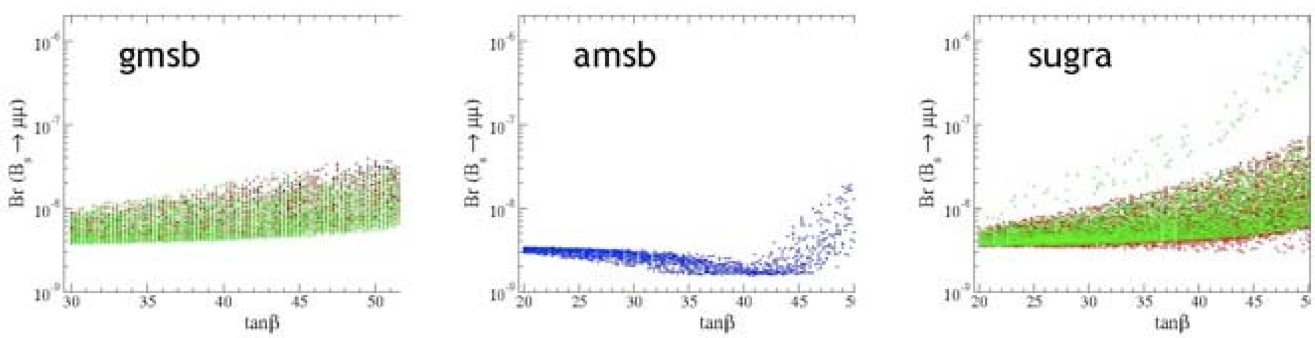
Mode	$B_s^0 \to \mu^+\mu^-$	$B_d^0 \to \mu^+\mu^-$	Reference
SM Expect.	3.5×10^{-9}	1.0×10^{-10}	Buras, 2003
CLEO	-	6.1×10^{-7}	PRD**62**, 091102
BELLE	-	1.6×10^{-7}	PRD**68**, 111101
CDF	5.8×10^{-7}	1.5×10^{-7}	PRL**93**, 032001
D0	4.1×10^{-7}	-	PRL**94**, 071802
BABAR	-	0.61×10^{-7}	PRL**94**, 221803
CDF	1.5×10^{-7}	0.39×10^{-7}	PRL**95**, 221805 + Err.
CDF	0.8×10^{-7}	0.23×10^{-7}	CDF public note 8176

- *B*-factories search also for
  - $B^0 \to e^+e^-$
  - $B^0 \to e^\pm\mu^\mp$
- SM branching ratio is very low:
  - $b\bar{b}$ cross section at LHC $\sim 10\times$ larger than at Tevatron
  - Events can be triggered at high luminosity

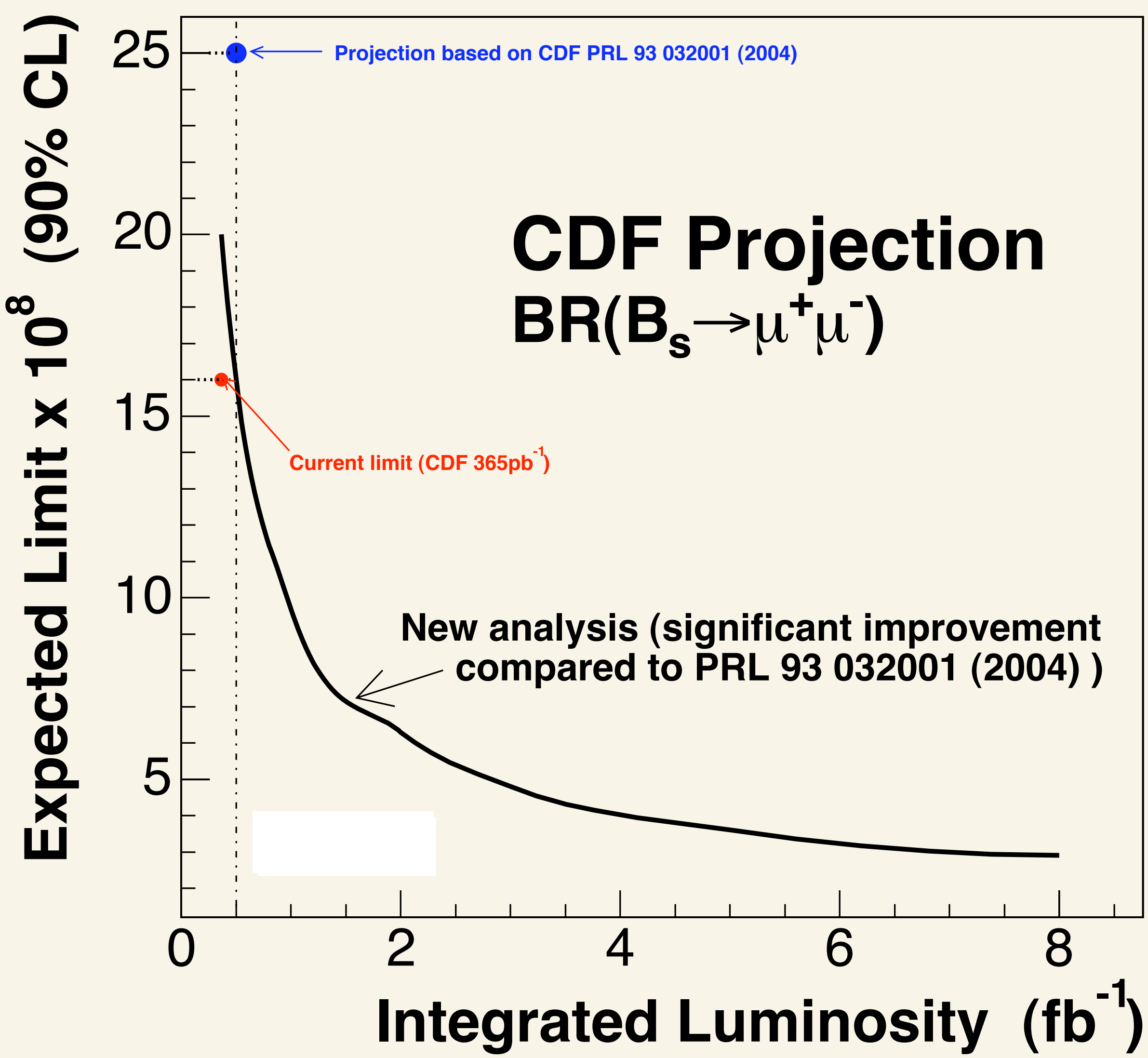


Conclusions

- First CMS update on search for $B_s^0 \to \mu^+\mu^-$ since 1999
  - ▹ Full reconstruction with pileup for $2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Expected upper limit in $10\,\mathrm{fb}^{-1}$: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq 1.4 \times 10^{-8}$
  - ▹ study limited by size of background MC sample
  - ▹ good mass resolution
- Outlook
  - ▹ include rare B decays
  - ▹ full analysis: likelihood selection and normalization sample



(from hep-ph/0310042)



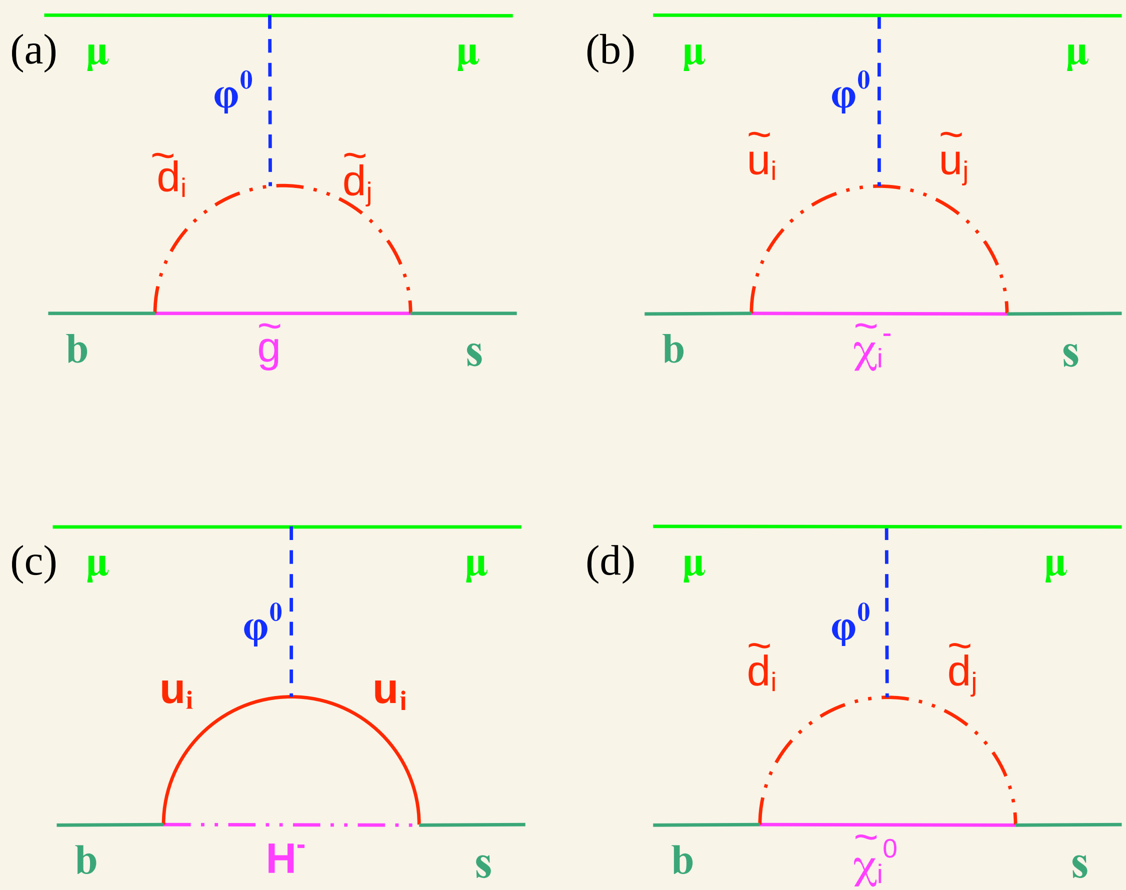
CDF Projection
BR($B_s \rightarrow \mu^+\mu^-$)
Projection based on CDF PRL 93 032001 (2004)
Current limit (CDF 365pb^{-1})
New analysis (significant improvement compared to PRL 93 032001 (2004))
Expected Limit x 10^8 (90% CL)
Integrated Luminosity (fb^{-1})
25
20
15
10
5
0
2
4
6
8

$B_s \to \mu^+\mu^-$ in the MSSM

We consider SUSY contributions from loop diagrams involving

- the charged Higgs boson,
- the charginos,
- the neutrinos, and
- the gluino.

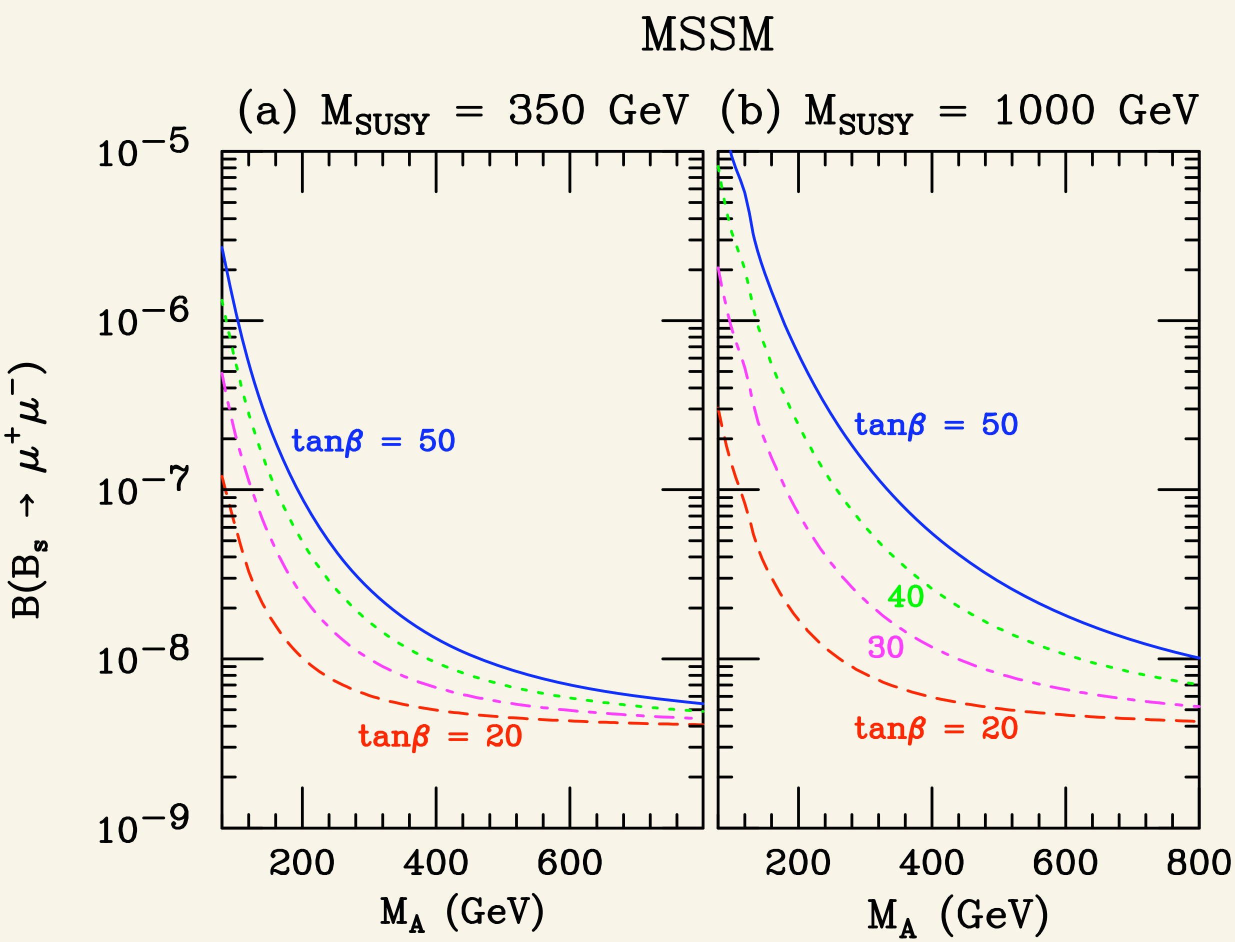
Feynman Diagrams



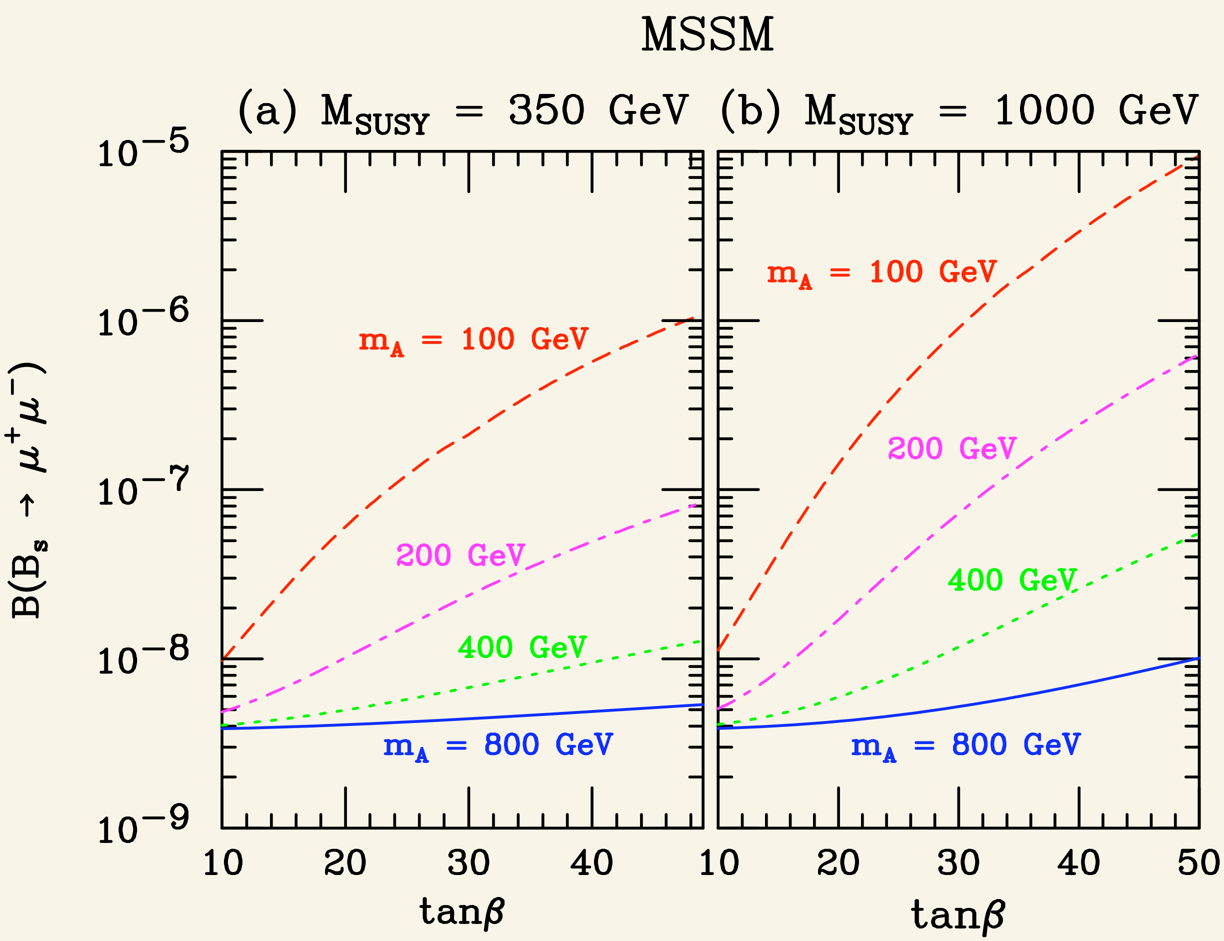
Recent Studies

- Mizukoshi, Tata and Wang (2002).
- Babu and Kolda (2000).
- Arnowitt, Dutta, Kamon and Tanaka (2002); Bobeth, Ewerth, Kruger and Urban (2002); Buras, Chankowski, Rosiek and Slawianowska (2002); Kane, Kolda and Lennon (2003; Dedes and Pilaftsis (2002); Dedes (2003); Dedes and Huffma (2004).
- Ellis, Olive and Spanos (2005); Ellis, Olive, Santoso and Spanos (2006).
- Isidori and Paradisi (2006).
- Carena, Menon, Noriega-Papaqui, Szynkman and Wagner (2006).

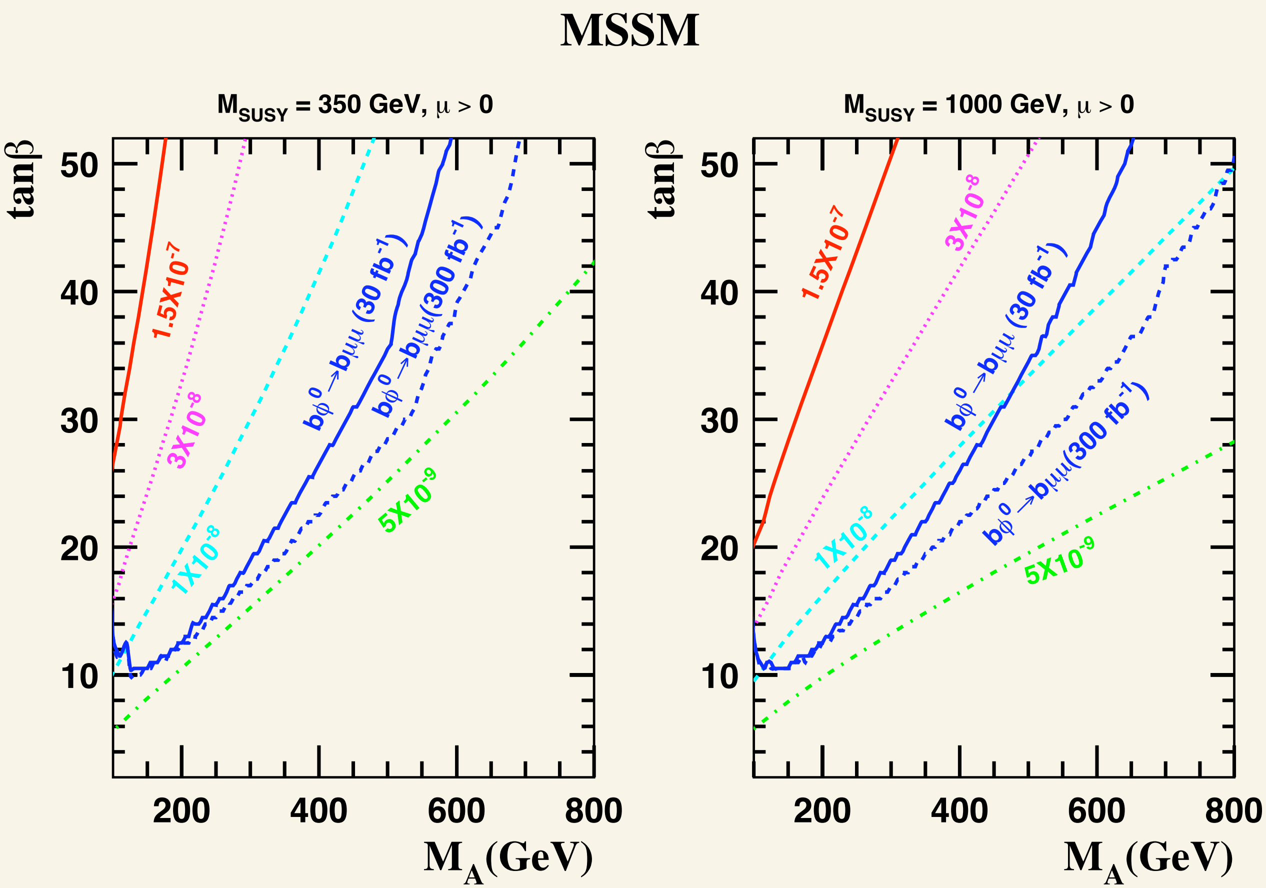
Branching Fraction versus m_A



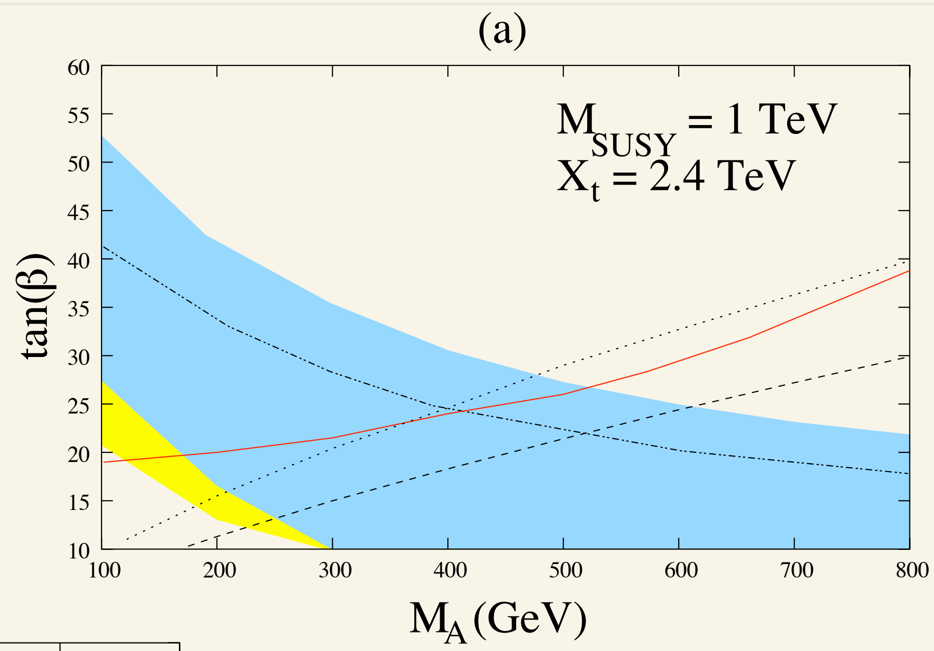
Branching Fraction versus tan(beta)

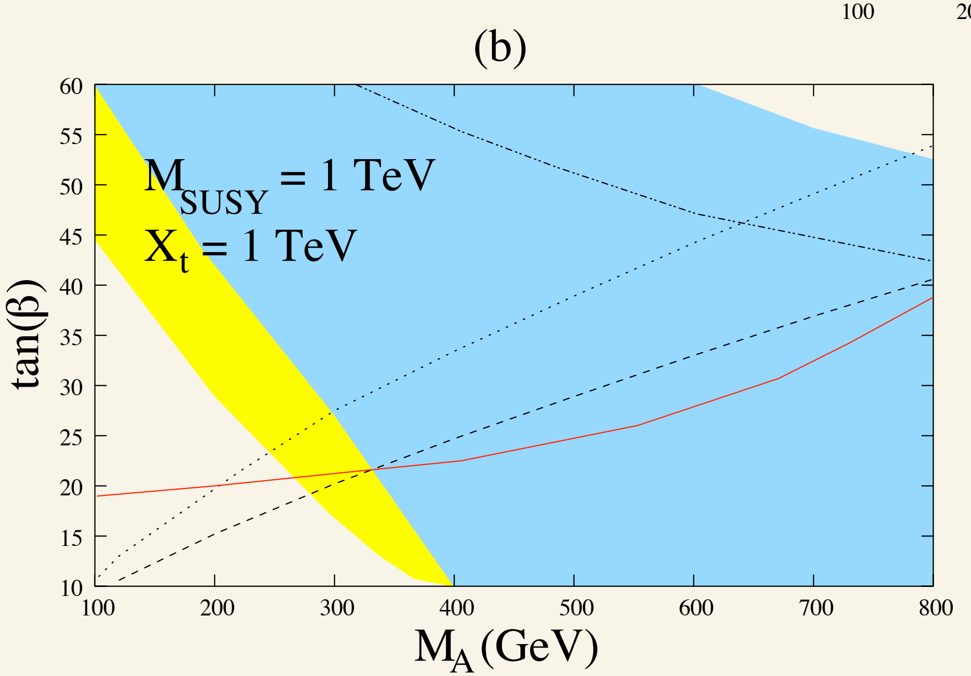


Minimal Supersymmetric Model



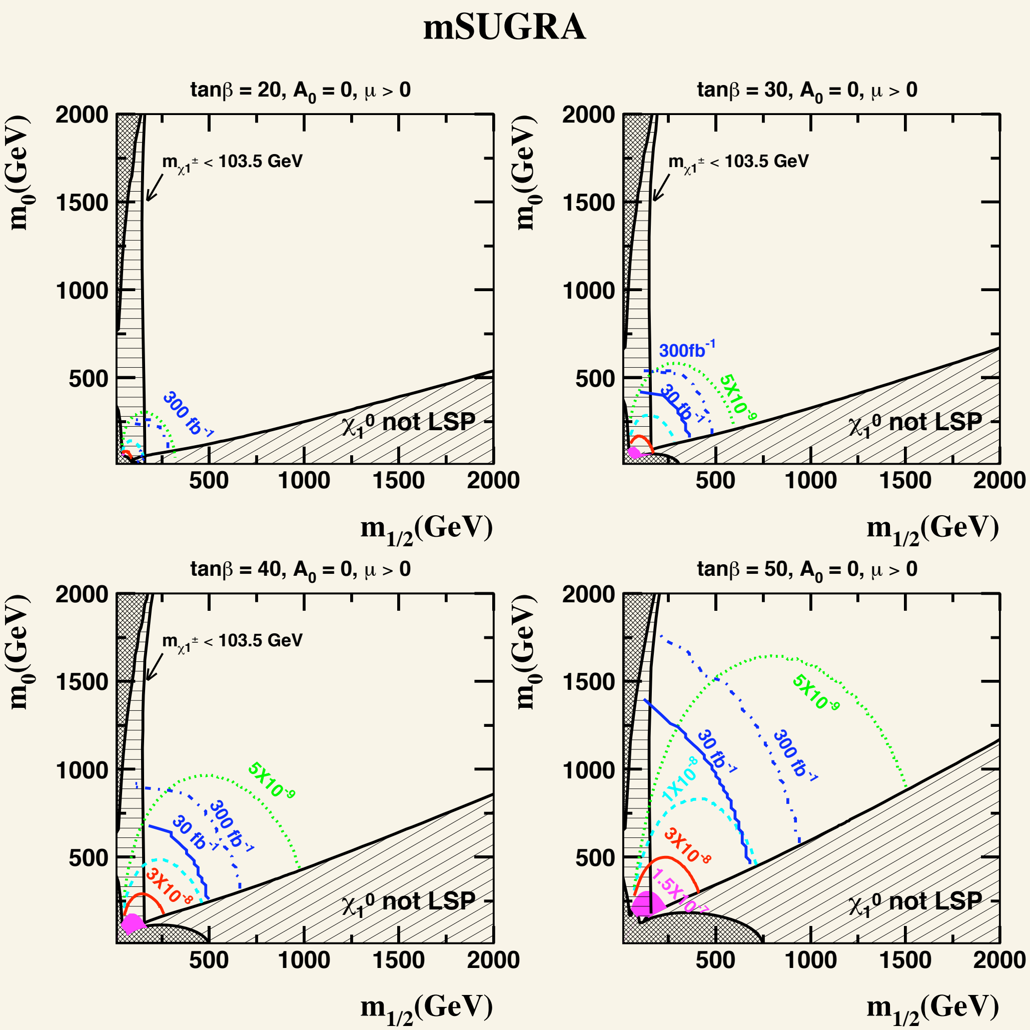
B_s to mu mu versus A^0,H^0 to tau tau





Carena, Menon, Noriega-Papaqui, Szynkman and Wagner, Phys. Rev. D **74**, 015009 (2006).

Minimal Supergravity Model



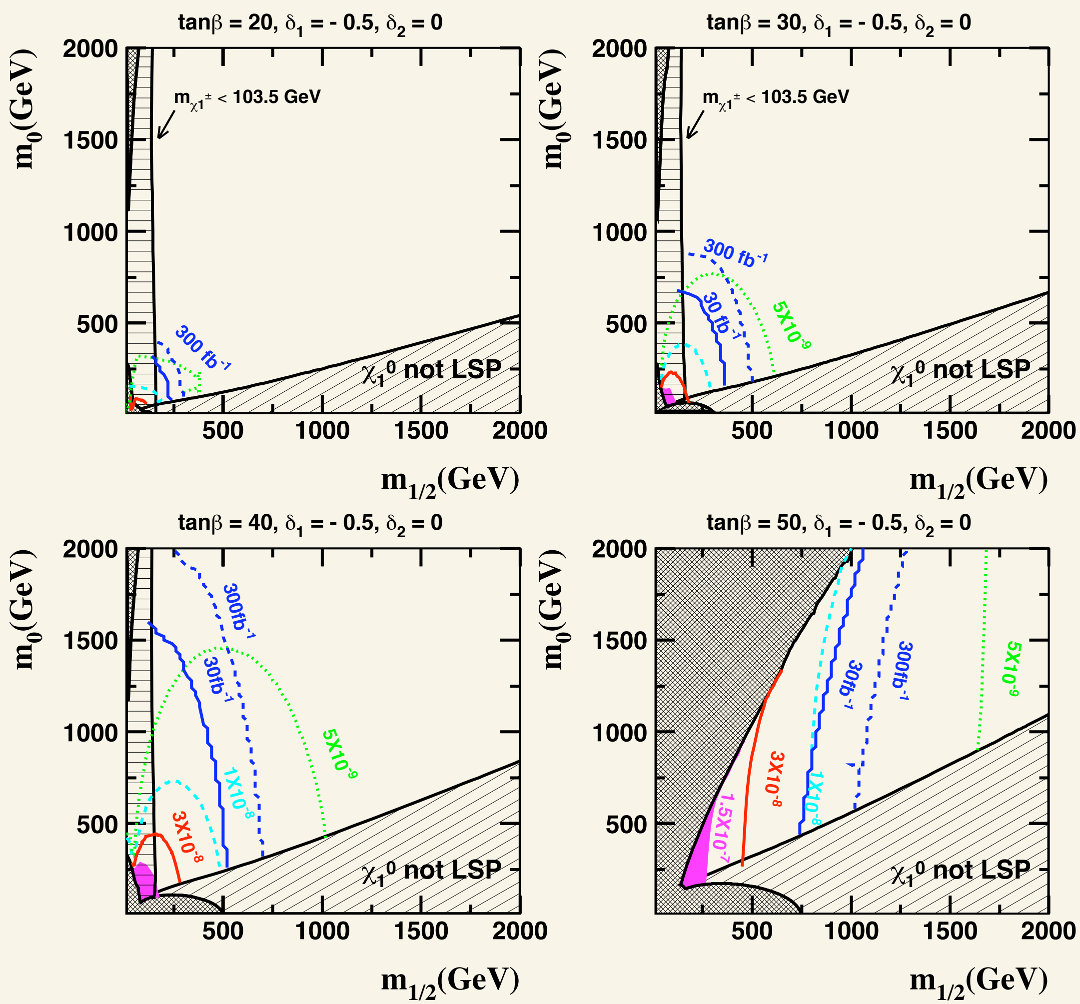
Non-universal Supergravity Models

- Supergravity models with non-universal Higgs boson masses (NUHM SUGRA) give more interesting rates.
- The Higgs masses at M_{GUT} are chosen to be
  $m^2_{H_i}(\mathrm{GUT}) = (1+\delta_i)m_0^2, i = 1, 2.$
- In our NUHM SUGRA cases, m_A and m_H are smaller than those in the mSUGRA model for the same values of m_0 and $m_{1/2}$.
- Consequently, both

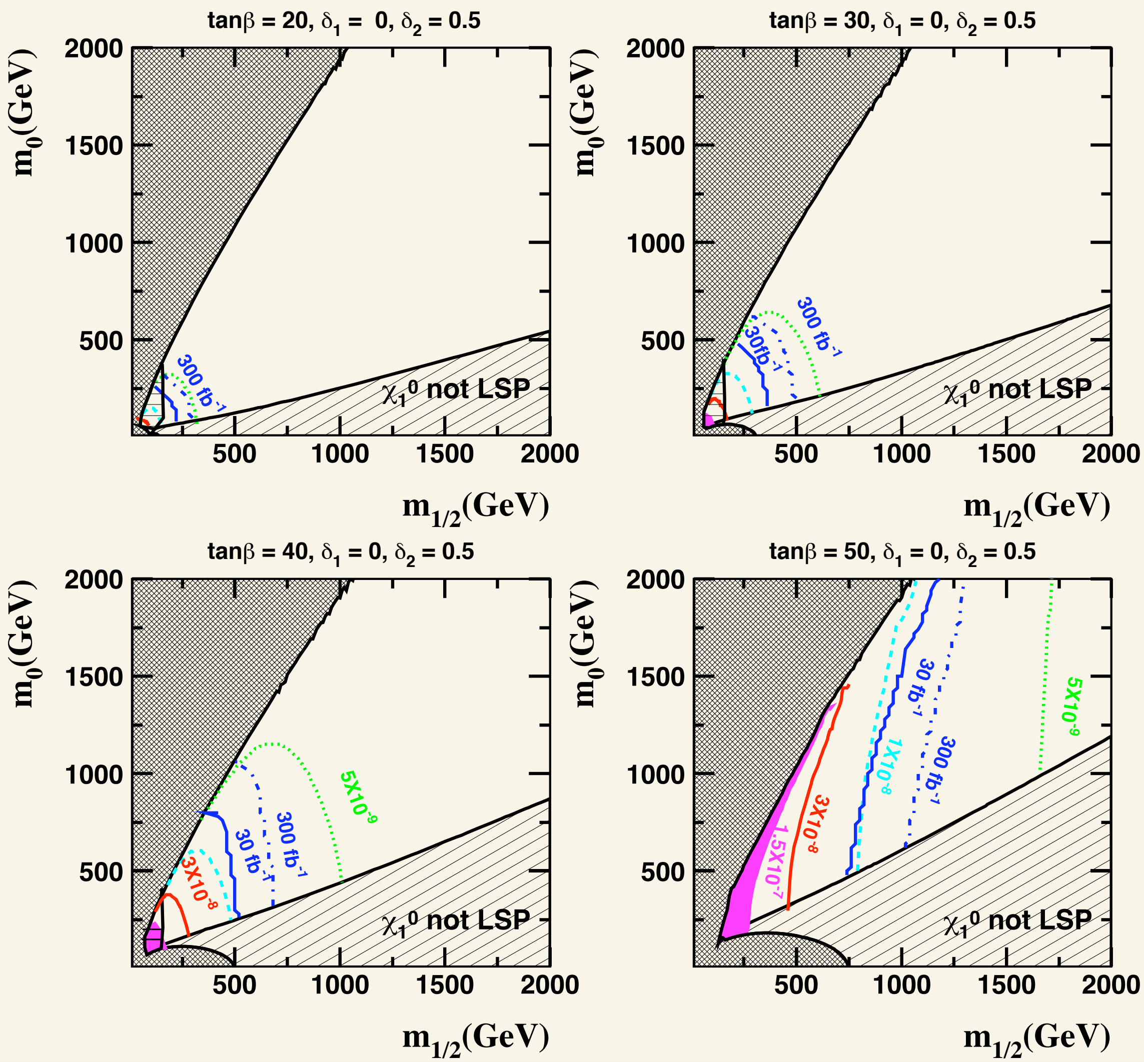
  $b\phi^0 \to b\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$

  will be able to cover regions of the parameter space with larger values of m_0 and $m_{1/2}$.

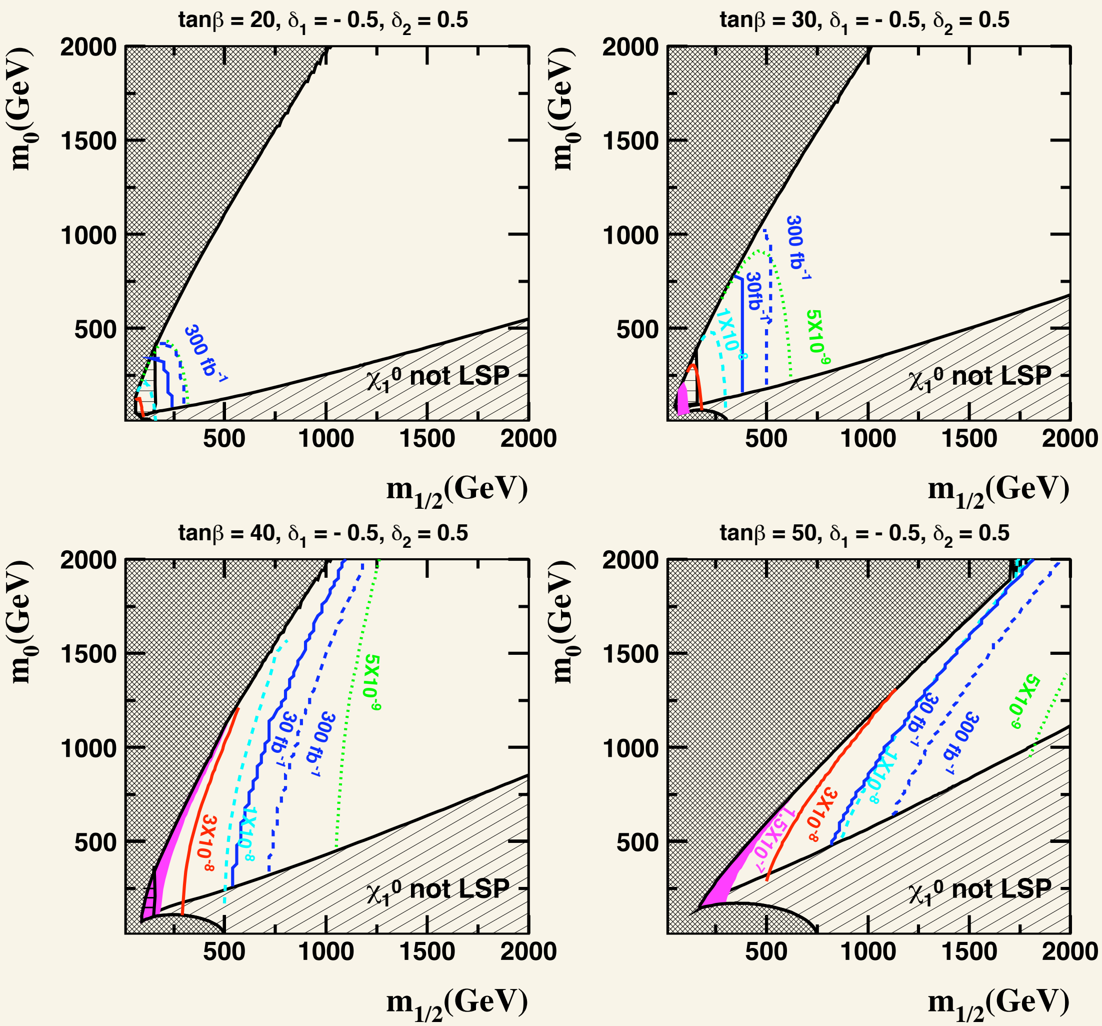
NUHM SUGRA Case I



NUHM SUGRA Case II



NUHM SUGRA Case III



Summary

(a) The contours for $\mathrm{B}(B_s \to \mu^+\mu^-) = 1 \times 10^{-8}$ in the parameter space are very close to the 5σ contours for $pp \to b\phi^0 \to b\mu^+\mu^- + X$, at the LHC with $L = 30$ fb^{-1}.

(b) The regions covered by $\mathrm{B}(B_s \to \mu^+\mu^-) \geq 5 \times 10^{-9}$ and the discovery region for $b\phi^0 \to b\mu^+\mu^-$ with 300 fb^{-1} are complementary in the mSUGRA parameter space.

(c) in SUGRA models with nonuniversal Higgs masses, a discovery for $\mathrm{B}(B_s \to \mu^+\mu^-) \simeq 5 \times 10^{-9}$ at the LHC will cover regions of the parameter space beyond the direct search for $pp \to b\phi^0 \to b\mu^+\mu^- + X$, with $L = 300$ fb^{-1}.